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Technical Report

CREEP AND SHRINKAGE OF REINFORCED THIN-SHELL CONCRETE

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CREEP AND SHRINKAGE OF REINFORCED THIN-SHELL CONCRETE

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by

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ABSTRACT

Creep coefficients and shrinkage factors were determined for specimens of three thin-shell reinforced concretes consisting of one normal-weight concrete, one sand–lightweight concrete, and one all-lightweight concrete. Prismatic specimens were tested in thicknesses of 1 inch, 2 inches, and 4 inches at stress–strength ratios of 0.25 and 0.50. Specimens were tested in controlled relative humidities of 25%, 50%, 70%, and 100%, with temperature at 73°F in all locations. Curves involving surface-area-to-volume ratios were used to determine time-dependent strains for different humidities, sizes, and stresses. Equations are presented for creep coefficients and for shrinkage; curves are presented for obtaining correction factors to be used in design equations. Correction curves for unit weight were developed with test data from this study. Predicted values for creep coefficients and shrinkage agreed with observed data when computed with equation and correction factors presented herein.

CONTENTS

INTRODUCTION

Several years ago studies were made at the Naval Civil Engineering Laboratory to determine long-time behavior of full-size prestressed concrete beams.[1-3] To supplement the information obtained from tests of the full-size beams, a study was made to relate the time-dependent strains of the beams to those of small, plain concrete cylinders made of concrete identical to that used in the beams.[4-6] To extend knowledge of time-dependent strains of thin shells and precast sections, creep and shrinkage studies were begun at NCEL in 1967 on small concrete prisms reinforced with mesh.

In curved shells, especially shallow ones of double curvature, creep and shrinkage strains can significantly alter shell stiffness and shell geometry (curvature), with a consequent increase in stresses and decrease in buckling resistance.[7-9] For example, buckling has occurred in certain shell structures several years after they were constructed.[10] Excessive long-time deflections have been observed in two buildings composed of precast thin-shell wall and roof panels.[11, 12] In one of the buildings[12] extensive cracking of the webs of the thin-shell panels was attributed, in part, to shrinkage strains. Thin-shell concrete construction has been shown to be economical for roofs,[13] and increased knowledge and control of creep and shrinkage should promote greater confidence in its use.

Although considerable research has been conducted by many investigators on creep and shrinkage of plain portland cement concrete and, to a lesser extent, of reinforced concrete beams, little comparable research has been accomplished for thin concrete sections with mesh reinforcement.

EXPERIMENTAL PROGRAM

Phase 1—Normal-Weight Concretes

Creep and shrinkage measurements were made on specimens of a normal-weight concrete fabricated in accordance with American Concrete Institute (ACI) Standard 525-63.[14] The concrete, with a design 28-day compressive strength of 5,000 psi and designated in this report as 8.25NW

(8.25 sacks of cement/yd^3, normal weight), was made with a nominal maximum size of aggregate of 3/8 inch, the maximum water content was 5 gallons per sack of cement, and the slump was 3 inches. The cement used was portland type III. The wet unit weight was about 145 pcf. Some strength factors and other details of the 8.25NW concrete are shown in the appendix.

Phase 2—Lightweight Concretes

Creep and shrinkage measurements were made on two lightweight concretes. One was a sand–lightweight concrete with 3/8-inch expanded shale as coarse aggregate and river sand as fine aggregate. This mix is designated in this report as 6.5SLW (6.5 sacks of cement/yd^3, sand–lightweight). The design compressive strength was 5,000 psi at an age of 14 days; the slump was 3 inches, the entrained air content ranged between 5% and 6%, and the cement was portland type III. The wet unit weight averaged about 112 pcf.

The second lightweight concrete, designated herein as 7LW (7 sacks of cement/yd^3, lightweight), utilized 3/8-inch expanded shale as coarse aggregate, but also had expanded shale sand as fine aggregate. The design compressive strength was 5,000 psi at an age of 14 days; the slump was 3 inches, the entrained air content ranged between 5% and 6%, and the cement was portland type III. The wet unit weight averaged about 99 pcf. Particulars of both lightweight concretes are presented in the appendix.

Phase 3—Miscellaneous Tests

A few specimens of 8.25NW concrete were tested without mesh reinforcement to determine the effects of the mesh on creep and shrinkage. At the close of the study, several of the specimens were broken and the amount of oxidation of the galvanized mesh was determined.

TEST SPECIMENS

Creep and shrinkage tests were performed on prismatic specimens. The test specimens (Figure 1) were 5 inches wide and 12 inches long and had thicknesses of 1 inch, 2 inches, or 4 inches. Each prism was reinforced with mesh consisting of no. 12 (0.10-inch diameter) or no. 14 (0.08-inch diameter) 2 x 2-inch galvanized welded wire fabric. Prisms 1 inch thick had one piece of the no. 14 fabric at midthickness, prisms 2 inches thick had one piece of the no. 12 fabric at midthickness, and prisms 4 inches thick had two pieces of no. 12 fabric placed at one-third and two-thirds thickness. Cutaway views of the forms with fabric in place are presented in Figure 2. The steel percentages (by cross-sectional area) were 0.30%, 0.22%, and 0.22% for the 1-inch, 2-inch and 4-inch-thick specimens, respectively. Test prisms for creep determination were loaded in spring-loaded compression frames as shown in Figure 3. The vertical ends of the prisms were coated with wax to prevent loss of moisture. Since moisture can leave (or enter) the concrete only on the exposed opposite faces, the prisms simulate thin shells of any length having thicknesses of 1 inch, 2 inches, or 4 inches. Nonloaded specimens from the same batches were provided for shrinkage determination. The tops and bottoms of the shrinkage specimens were also coated with wax. Testing began on all specimens after 14 days of curing in 100% RH (specimens were 14 days old).

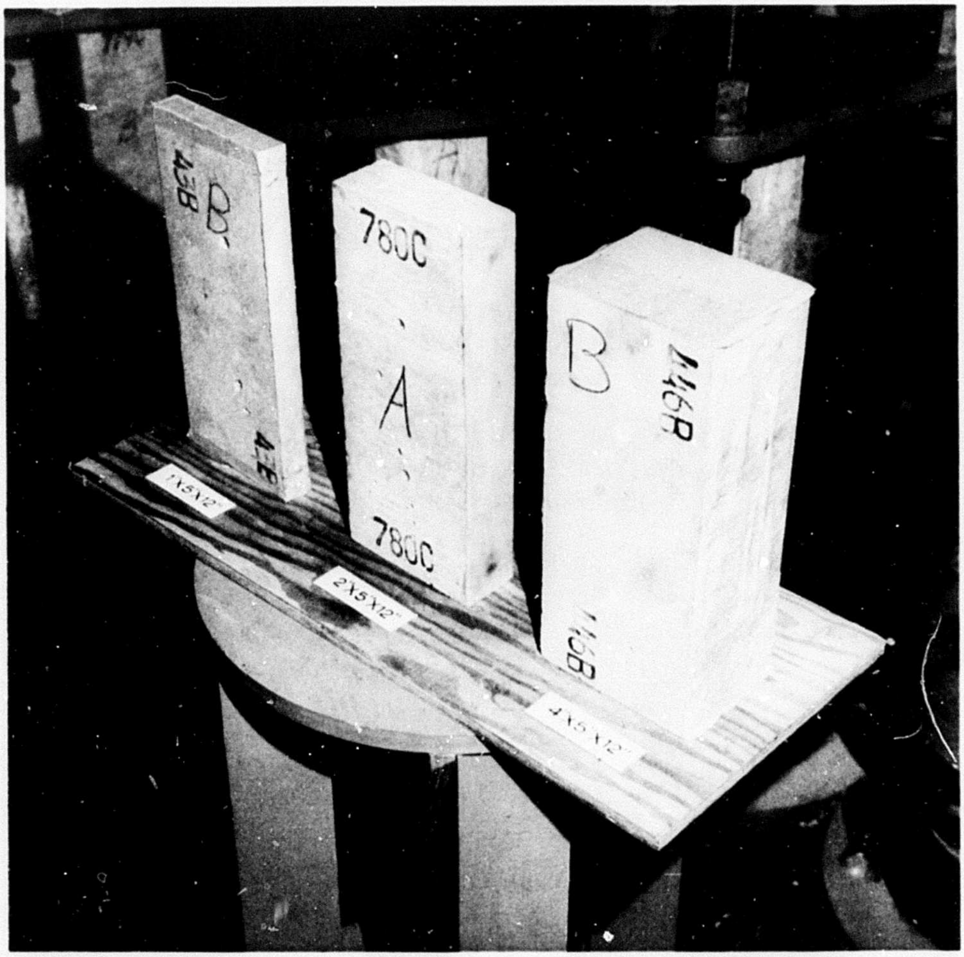


Figure 1. Prismatic test specimens.

DEFORMATION MEASUREMENTS

Time-dependent deformation measurements were made with a 5-inch fulcrum-plate mechanical strain gage over the central longitudinal portion of the two 5 x 12-inch faces of each specimen. Insert screws with holes for the points of the gage were cast in place. The insert screws can be seen in the cutaway views in Figure 2. Strain was calculated by dividing the deformation by the gage length (5 inches).

DEFINITION OF TERMS

Terms used in this report are defined as follows:

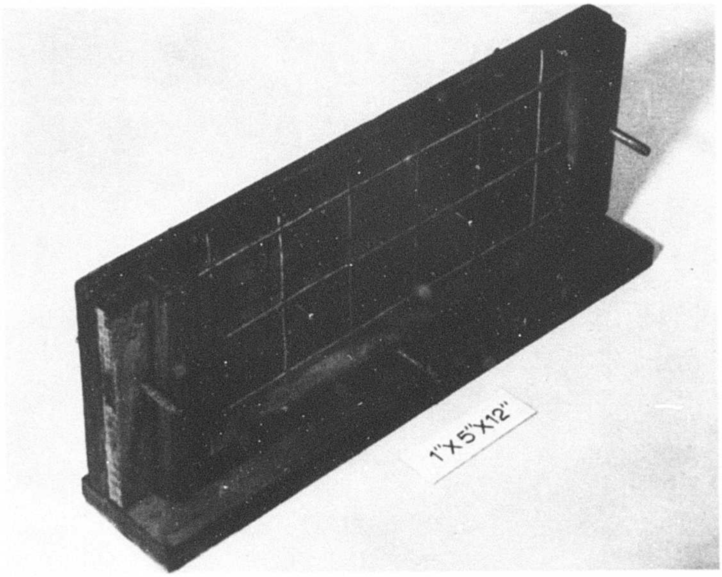
Creep-plus-shrinkage — the time-dependent strain in a loaded concrete specimen resulting from the combination of an external load and the effects of drying or wetting. Measurement of creep-plus-shrinkage began immediately after the load was applied; therefore the initial strain caused by application of the load was not included.

Shrinkage — time-dependent strain in a nonloaded concrete specimen which is subjected to either drying or wetting. Drying causes a specimen to undergo a compressive strain called "positive shrinkage" or simply "shrinkage"; wetting causes a specimen to "swell" or to undergo a tensile strain called "swellage" or "negative shrinkage."

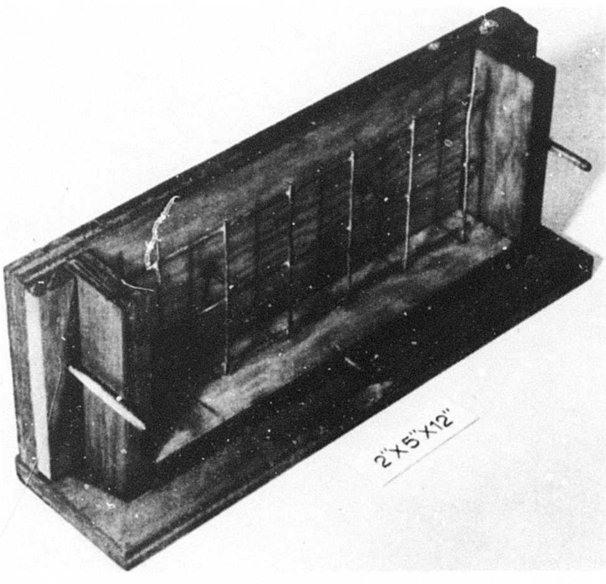
Creep — "the time-dependent part of strain resulting from [the application of] force."[15] Creep is the quantity resulting when shrinkage is subtracted from creep-plus-shrinkage.

Stress–strength ratio — the ratio of the applied stress on a specimen to the estimated ultimate compressive strength (f'_c) of that specimen at the time it was loaded. The f'_c value is determined from compressive strength tests on identical companion specimens from the same batch of concrete as those specimens to be loaded.

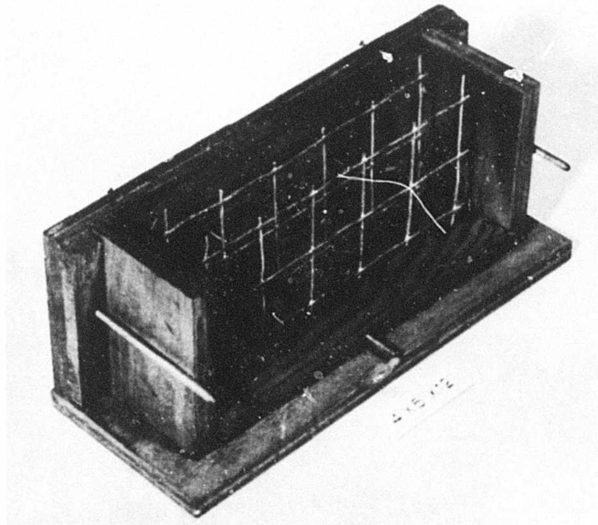
Time-dependent strain — a term which may include creep-plus-shrinkage, shrinkage, or creep, or any combination of them.



(a) Form for specimens 1 inch thick.



(b) Form for specimens 2 inches thick.



(c) Form for specimens 4 inches thick.

Figure 2. Forms for prismatic specimens showing mesh reinforcement.

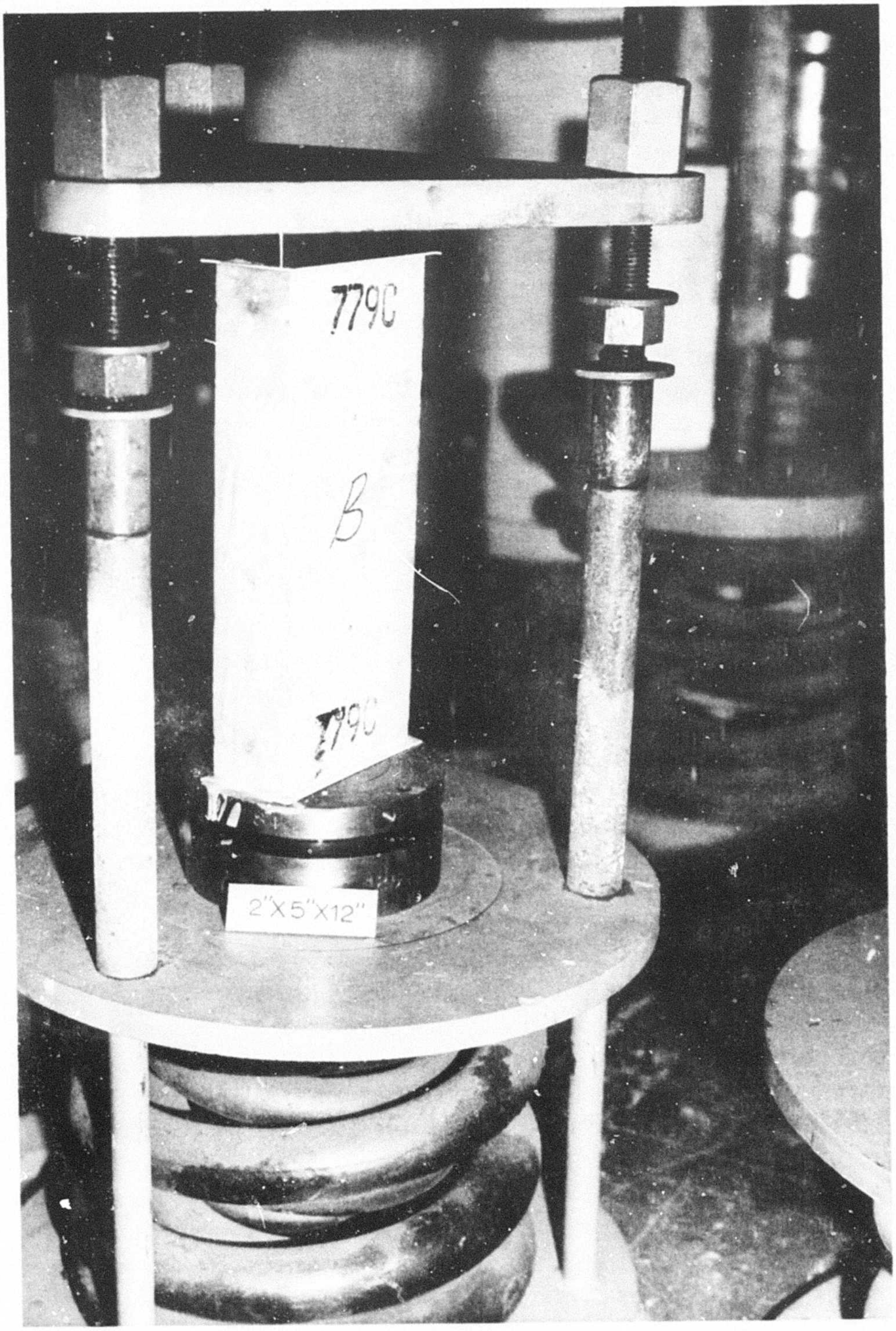


Figure 3. A 2-inch-thick prism under load in a creep frame.

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EXPERIMENTAL RESULTS

Phase 1—8.25NW Concrete

The experimental program for 8.25NW concrete is shown in Table 1. No fewer than three specimens were tested under each of the variables of specimen thickness, storage humidity, and stress–strength ratio. Test results for creep-plus-shrinkage (loaded specimens) and shrinkage (nonloaded specimens), together with calculated values for creep, are presented in Table 2. The time-dependent strains shown in Table 2 are curve values obtained from averages of multiple specimens.

The effects of specimen thickness on shrinkage are shown in Figure 4. The size of the specimen affects both the rate and ultimate value of shrinkage in all humidities, with the smallest specimens exhibiting highest shrinkage. The reinforcing steel percentage for the 1-inch-thick specimens was 0.30% compared to 0.22% for the 2- and 4-inch-thick specimens. Had the 1-inch-thick specimens contained the lesser amount of steel (0.22%), their shrinkage values would have been higher than those shown in Figure 4. Shrinkage strain in a drying humidity is compressive; however, in 100% RH the hardened concrete eventually absorbs water. The absorption of water causes the specimen to swell in all directions; when measured by strain gages in one direction, this swellage amounts to a lengthening of the specimen (or negative shrinkage).

The effects of storage humidity on shrinkage of specimens 2 inches thick are shown in Figure 5; similar results are seen for the 1- and 4-inch-thick specimens. The range of most dramatic effects of humidity upon shrinkage is between 70% RH and 100% RH. The shrinkage for any humidity between 25% RH and 100% RH can be obtained from curves such as those shown in Figure 5 (constructed with data from Table 2).

Typical examples of the effects of specimen thickness on creep-plus-shrinkage are shown in Figure 6. Based on previous work at NCEL[4,5] creep-plus-shrinkage at 0.50 f'_c should increase only about 3% between 365 days and 2-1/2 years. Typical stress versus time-dependent strain curves are shown in Figure 7 for specimens 2 inches thick in 70% RH. Nonlinearity between stress and creep-plus-shrinkage was found throughout the test period of 365 days. Values for creep-plus-shrinkage at 0.00 f'_c are shrinkage strains (see Table 2). Relationships such as those shown in Figure 7 can be used to determine creep-plus-shrinkage for any stress–strength ratio between 0.00 and 0.50. When these types of curves are prepared for specimens in each humidity, the relationships can be developed as shown in Figure 8, which presents the effects of humidity upon creep-plus-shrinkage for specimens 2 inches thick. From the curves of Figure 8, creep-plus-shrinkage can be determined for any relative humidity between 25% and 100%.

Table 1. Experimental Program for Phase 1, 8.25NW Concrete

Thickness[a] (in.)	Storage Environment[b] (% RH)	No. of Loaded Specimens at Stress–Strength Ratio of—		No. of Nonloaded (Shrinkage) Specimens
		0.50	0.25	
1	25	4	3	5
1	70	4	4	6
1	100	4	4	5
2	25	3	3	3
2	70	4	4	4
2	100	4	4	4
4	25	4	3	6
4	70	4	4	6
4	100	4	4	7

[a] All specimens were prisms with a width of 5 inches and a length of 12 inches, the variable was thickness.

[b] Temperature of all environments was 73°F, specimens were loaded (or installed) after 14 days of curing in 100% RH.

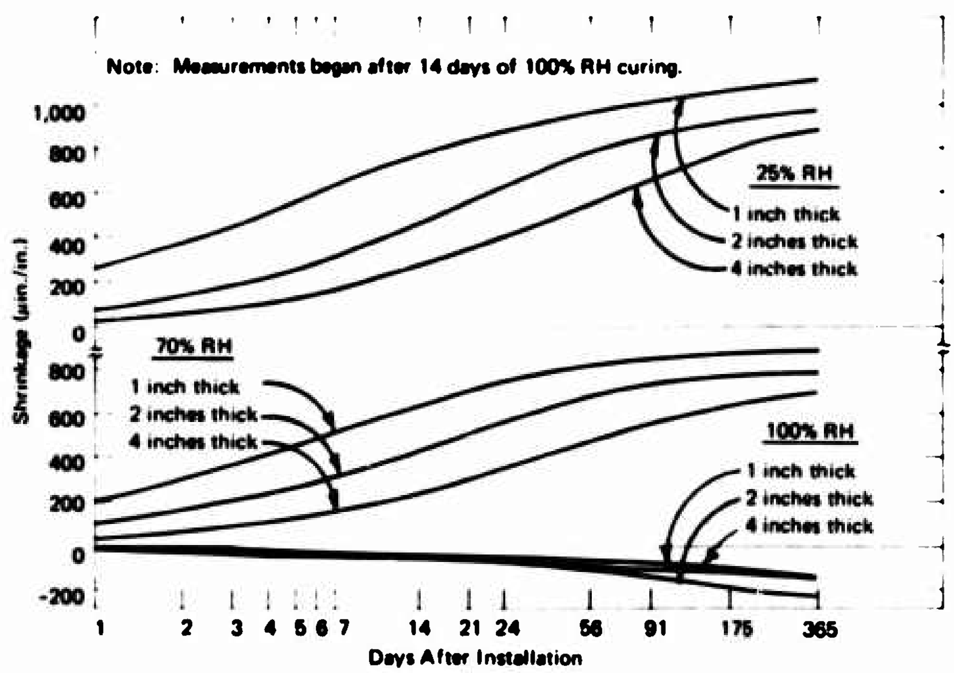


Figure 4. Effects of specimen thickness on shrinkage, 8.25NW concrete.

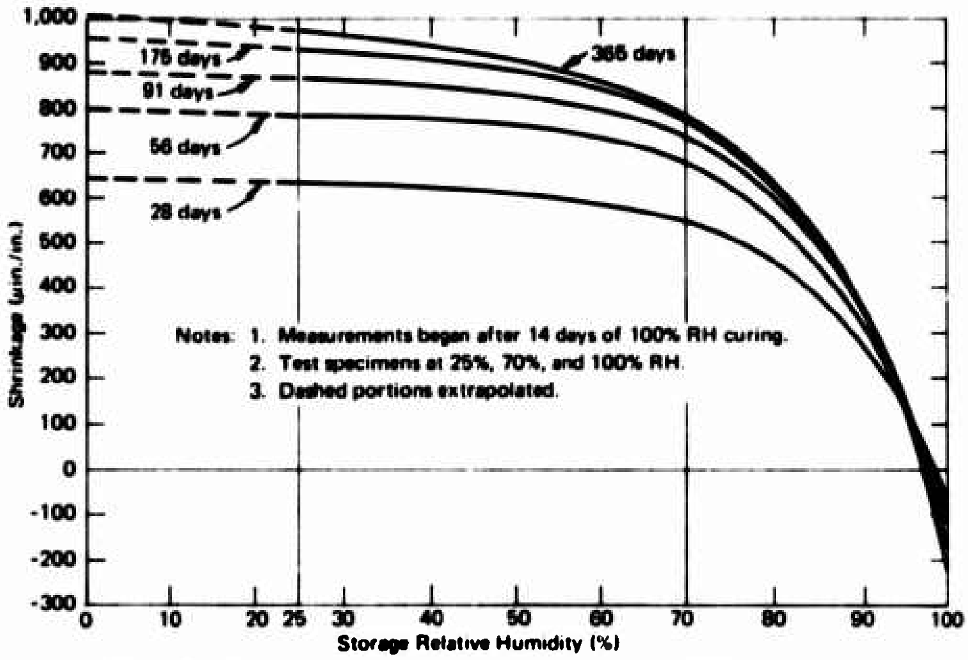


Figure 5. Effects of storage humidity on shrinkage, 8.25NW concrete specimens 2 inches thick.

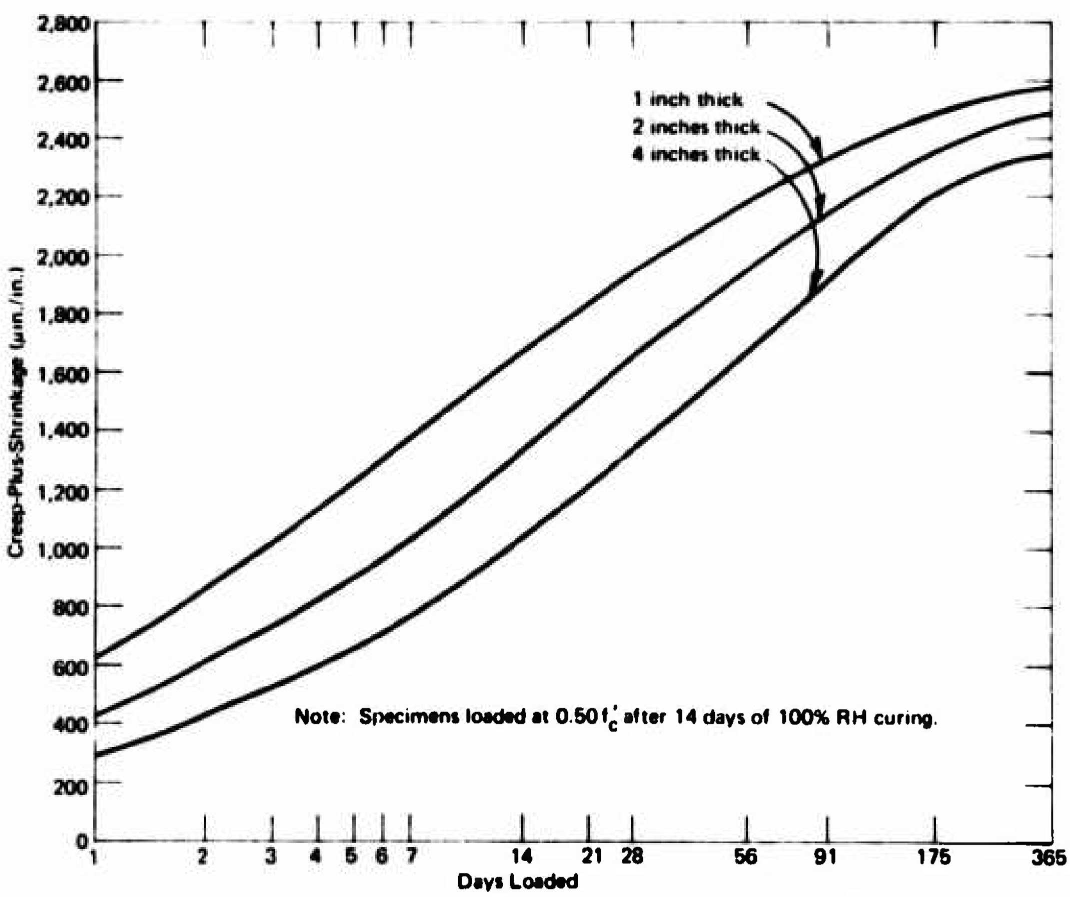


Figure 6. Effects of specimen thickness on creep-plus-shrinkage, 8.25NW concrete in 70% RH.

Table 2. Creep-Plus-Shrinkage, Shrinkage, and Creep for 8.25NW Concrete

Parameter	Stress–Strength Ratio	Storage Environment (% RH)	Strain Values[a] (μin./in.) for Specimens Loaded—							
			7 Days	14 Days	21 Days	28 Days	56 Days	91 Days	175 Days	365 Days
1-Inch-Thick Specimens										
Creep-Plus-Shrinkage	0.50	25	1,475	1,890	2,125	2,255	2,500	2,650	2,780	2,865
		70	1,370	1,685	1,850	1,950	2,175	2,325	2,480	2,580
		100	415	490	535	565	645	710	795	865
	0.25	25	1,010	1,255	1,390	1,480	1,630	1,695	1,785	1,865
		70	765	940	1,045	1,105	1,250	1,330	1,400	1,440
		100	150	195	215	235	275	300	335	360
Shrinkage[b]	0.00	25	640	775	835	875	965	1,020	1,070	1,115
		70	520	635	740	745	825	850	875	885
		100	-30	-45	-60	-70	-95	-110	-130	-150
Creep[c]	0.50	25	835	1,115	1,290	1,380	1,535	1,630	1,710	1,750
		70	850	1,050	1,110	1,205	1,350	1,475	1,605	1,695
		100	445	535	595	635	740	820	925	1,015
	0.25	25	370	480	555	605	665	675	715	750
		70	245	305	305	360	425	480	525	555
		100	180	240	275	305	370	410	465	510
2-Inch-Thick Specimens										
Creep-Plus-Shrinkage	0.50	25	1,135	1,530	1,780	1,950	2,325	2,530	2,735	2,855
		70	1,040	1,330	1,510	1,640	1,940	2,130	2,360	2,490
		100	505	570	625	670	785	870	1,005	1,135
	0.25	25	690	935	1,095	1,220	1,510	1,650	1,770	1,855
		70	555	730	850	940	1,140	1,265	1,380	1,440
		100	185	225	245	265	305	335	395	455
Shrinkage[b]	0.00	25	320	470	565	635	785	865	930	975
		70	315	420	490	550	680	735	770	785
		100	-30	-45	-55	-70	-100	-130	-180	-220
Creep[c]	0.50	25	815	1,060	1,215	1,315	1,540	1,665	1,805	1,880
		70	725	910	1,020	1,090	1,260	1,395	1,590	1,705
		100	535	620	680	740	885	1,000	1,185	1,355
	0.25	25	370	465	530	585	725	785	840	880
		70	240	310	360	390	460	530	610	655
		100	215	270	300	335	405	465	575	675

continued

Table 2. Continued

Parameter	Stress–Strength Ratio	Storage Environment (% RH)	Strain Values[a] (μin./in.) for Specimens Loaded—							
			7 Days	14 Days	21 Days	28 Days	56 Days	91 Days	175 Days	365 Days
4-Inch-Thick Specimens										
Creep-Plus-Shrinkage	0.50	25	950	1,245	1,445	1,590	1,960	2,215	2,565	2,765
		70	765	1,035	1,210	1,345	1,680	1,910	2,210	2,345
		100	510	620	690	735	850	925	1,035	1,160
	0.25	25	465	690	840	945	1,195	1,365	1,575	1,730
		70	395	550	655	735	945	1,095	1,270	1,365
		100	175	230	270	290	345	390	440	500
Shrinkage[b]	0.00	25	170	275	345	400	545	650	790	890
		70	165	250	310	350	475	555	640	695
		100	-30	-40	-45	-50	-65	-80	-105	-145
Creep[c]	0.50	25	780	970	1,100	1,190	1,415	1,565	1,775	1,875
		70	600	785	900	995	1,205	1,355	1,570	1,650
		100	540	660	735	785	915	1,005	1,140	1,305
	0.25	25	295	415	495	545	650	715	785	840
		70	230	300	345	385	470	540	630	670
		100	205	270	315	340	410	470	545	645

[a] When multiple specimens were tested, value represents average.

[b] Negative shrinkage is swellage.

[c] Creep was obtained by subtracting shrinkage from creep-plus-shrinkage.

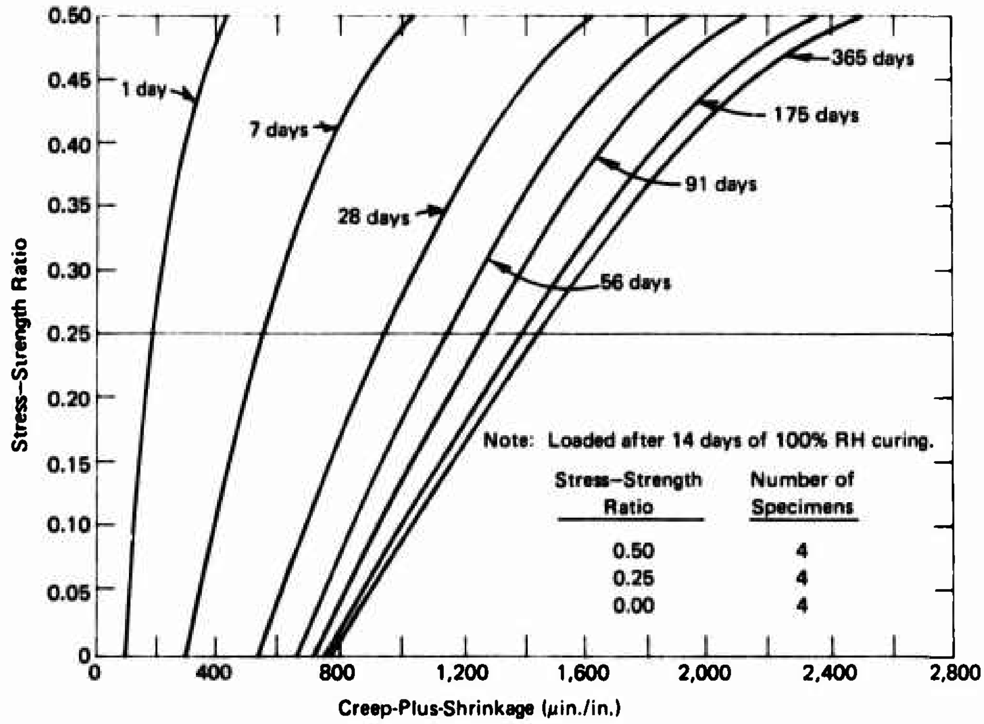


Figure 7. Stress–time-dependent strain for 8.25NW concrete specimens 2 inches thick in 70% RH.

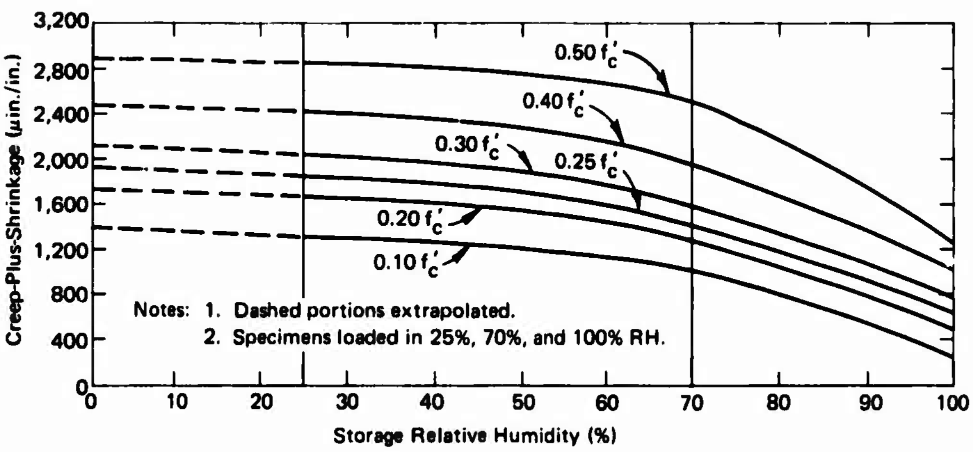
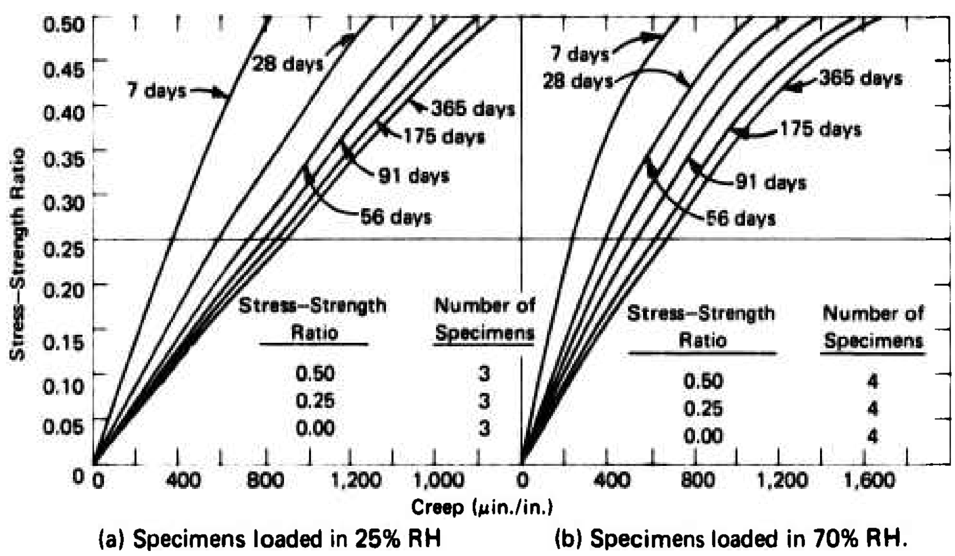


Figure 8. Creep-plus-shrinkage versus humidity for 8.25NW concrete specimens 2 inches thick after 365 days of loading.

Stress versus creep relationships for specimens 2 inches thick in 25% RH and 70% RH are presented in Figure 9. Greater deviation from a straight line is apparent in 70% RH than in 25% RH. Stress—creep relationships for 1- and 4-inch-thick specimens are similar to those shown in Figure 9.



Note: Specimens loaded after 14 days of 100% RH curing.

Figure 9. Stress versus creep for 8.25NW concrete specimens 2 inches thick.

The effects of humidity on creep-plus-shrinkage, shrinkage, and creep for specimens 2 inches thick are shown in Figure 10 for specimens loaded at $0.25 f'_c$ and in Figure 11 for specimens loaded at $0.50 f'_c$. In Figure 10 the curves for creep-plus-shrinkage and for shrinkage indicate reasonable relationships with respect to humidity, but the curve for creep (creep-plus-shrinkage minus shrinkage) between 70% RH and 100% RH shows more creep at 100% RH than at any humidity between the two. Curves like this one for creep versus humidity, particularly at lower stresses, reveal the inherent weakness in the practice of determining creep by subtracting shrinkage from creep-plus-shrinkage. A rational analysis reveals no way to substantiate higher creep in 100% RH than in a lower humidity. Nevertheless, some designers still use separate terms for creep and for shrinkage, so consideration is given to these terms as well as to creep-plus-shrinkage in the design applications section of this report.

As reported in Reference 4, creep-plus-shrinkage, creep, and shrinkage data from laboratory specimens can be used to predict, with reasonable accuracy, the time-dependent strains to be expected in full-size members of similar concrete. This prediction is accomplished on the basis of the ratio of exposed surface area to volume (S/V) of the laboratory specimens and of the larger

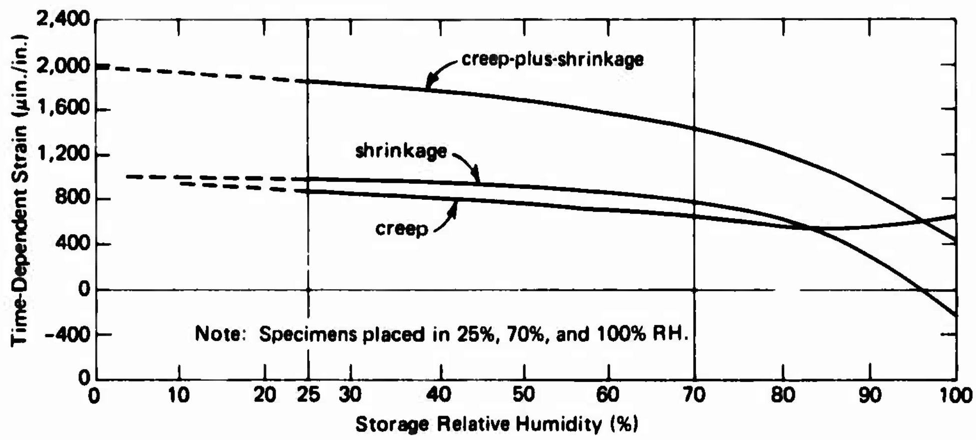


Figure 10. Effects of humidity on time-dependent strains, 8.25NW concrete specimens 2 inches thick loaded at 0.25 f_c' for 365 days.

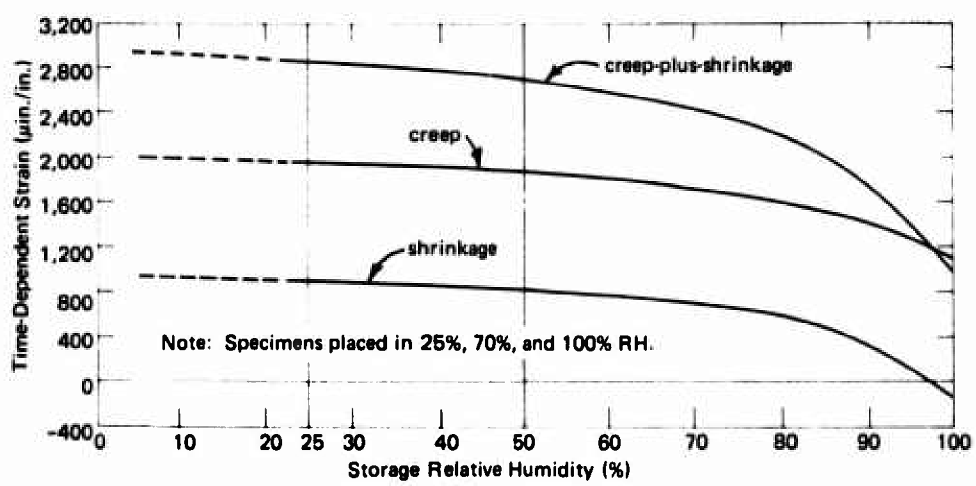
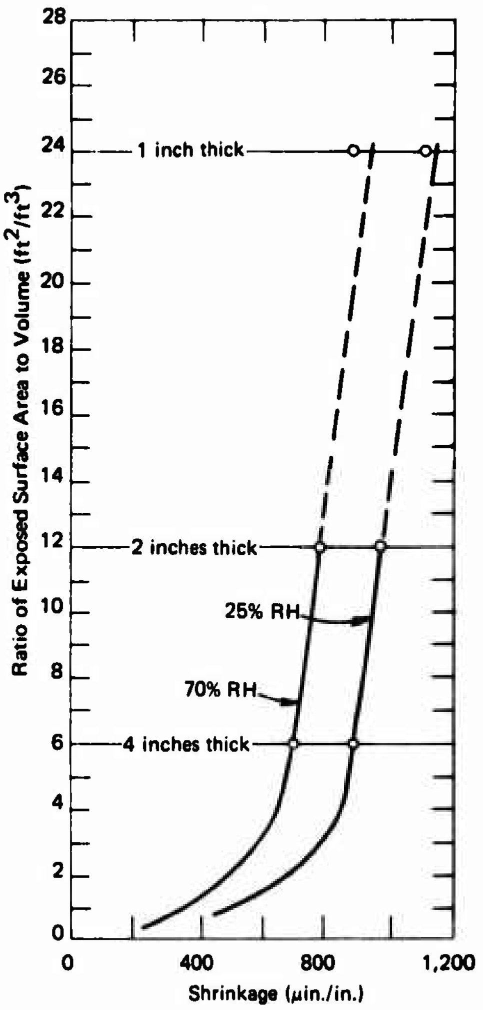


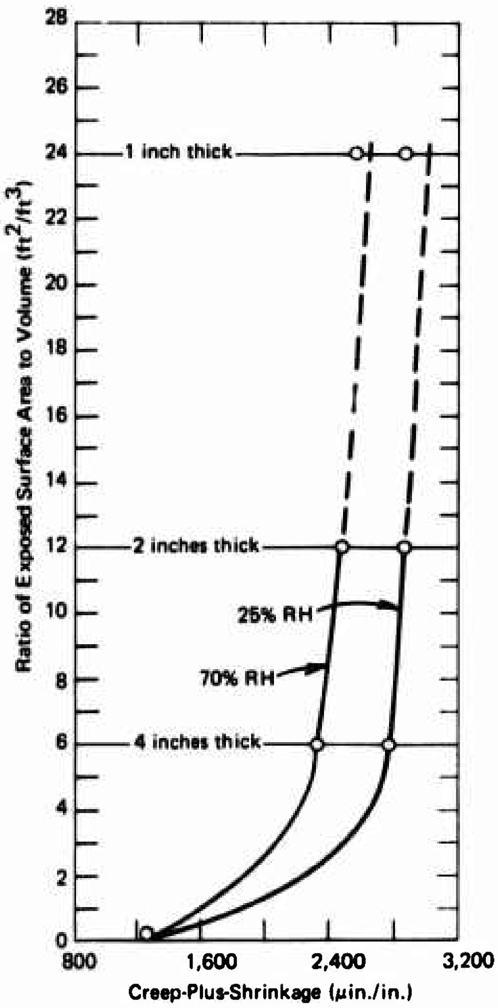
Figure 11. Effects of humidity on time-dependent strains, 8.25NW concrete specimens 2 inches thick loaded at 0.50 f_c' for 365 days.

members. Prediction curves for shrinkage, constructed from test data for 8.25NW concrete obtained in this study, are shown in Figure 12. The **S/V** values for the 1-, 2-, and 4-inch-thick specimens are 24.0, 12.0, and 6.0, respectively. Moisture was lost from the test specimens only on the 5 x 12-inch faces, thus simulating a continuous shell with the thickness being the only variable. The two prediction curves shown in Figure 12 define the drying humidity limits of the research study (25% RH and 70% RH). Shrinkages of similar shells at relative humidities between 25% RH and 70% RH would lie between the two curves. **S/V** curves of creep-plus-shrinkage, similarly constructed, are shown in Figure 13.



Notes: 1. Reinforcement for specimens 1 inch thick was 0.30%.
2. Reinforcement for specimens 2 inches and 4 inches thick was 0.22%.
3. Data represent shrinkage at 365 days.
4. Dashed portions are estimations.

Figure 12. Shrinkage prediction chart.



Notes: 1. Reinforcement for specimens 1 inch thick was 0.30%.
2. Reinforcement for specimens 2 inches and 4 inches thick was 0.22%.
3. Data represent total creep at $0.50 f_c'$ after 365 days.
4. Dashed portions are estimations.

Figure 13. Creep-plus-shrinkage prediction chart.

Phase 2—Lightweight Concretes

6.5SLW Concrete. The experimental program for 6.5SLW concrete is outlined in Table 3. Creep-plus-shrinkage, shrinkage, and creep are shown in Table 4. As before, creep was calculated by subtracting shrinkage from creep-plus-shrinkage. Creep-plus-shrinkage for 2- and 4-inch-thick specimens loaded at 0.25 f'_c in 100% RH show unexpected decreases in later ages.

These decreases were probably the result of the extraction of absorbed water from the highly absorptive expanded-shale coarse aggregate. When the concrete was mixed, and for some period thereafter, the coarse aggregate absorbed a relatively large amount of water. As cement hydration proceeds, free water inside the hardening concrete is gradually dissipated, causing a relatively dry environment internally. The relative interior dryness establishes a vapor pressure difference (hydraulic gradient) between inside (lower pressure) and outside (higher pressure) of the concrete. Since the exterior environment involved is 100% RH, water begins to move into the concrete from the outside, but at the same time the water previously absorbed by the lightweight aggregate is also subjected to the pressure gradient and begins to move into the surrounding hardened cement paste. As water movement begins into the concrete from outside as well as into the paste from the aggregate, the internal humidity is again raised, thus lowering the vapor pressure and tending to reestablish equilibrium. As the concrete absorbs water, it swells, or lengthens; the degree of lengthening is dependent upon the amount of compressive stress on the concrete. In a nonloaded (shrinkage) specimen in 100% RH (Table 4), swellage (negative shrinkage) began almost immediately because there was no hydraulic pressure gradient to overcome resulting from an applied load. In loaded specimens swellage begins after the hydraulic pressure gradient is overcome by continual internal drying of the concrete. The true quantity of swellage in a loaded specimen is unknown because the concrete is creeping compressively while at the same time water is entering the concrete, tending to make it swell. The fact is, the swellage serves to decrease the amount of creep which would have occurred had there been no swellage. It appears that the combination of low stress level (0.25 f'_c) and extra water coming from the aggregate resulted in a net decrease in creep-plus-shrinkage and creep.

The effects of specimen thickness on shrinkage are shown in Figure 14, which is similar to Figure 4 for normal-weight concrete. In 25% RH the effects of thickness are similar to those for normal-weight concrete, that is, the smallest specimens have highest shrinkage. In 50% RH the relationships are rather confused; shrinkage of the 1-inch-thick specimens in the beginning was highest of the three but soon was exceeded by the shrinkage of the 2-inch-thick specimens and was eventually exceeded also by that of the 4-inch-thick specimens. The author believes that this reduction in net shrinkage results from the combined effects of the greater percentage of reinforcement in the 1-inch-thick specimens and removal of moisture from the aggregate. Other things being equal, swellage caused by water coming from the lightweight aggregate would have a greater effect quantitatively in the smaller specimens.[4] Shrinkage in 100% RH showed relationships similar to those for normal-weight concrete (Figure 4).

Effects of humidity on creep-plus-shrinkage, shrinkage, and creep are shown in Figures 15 and 16 for specimens 2 inches thick loaded at $0.25 f'_c$ and at $0.50 f'_c$, respectively. As observed earlier, humidity affects time-dependent strains most dramatically between 70% RH and 100% RH. Quantitatively, there is not much difference in any of the curves between 50% RH and 25% RH.

The effects of stress–strength ratio on creep-plus-shrinkage in 50% RH are presented in Figure 17. As observed before, there is distinct nonlinearity, especially above a stress–strength ratio of 0.25. The same types of relationships are observed in Figure 18 for creep of specimens 2 inches thick in 25% RH and 50% RH.

Table 3. Experimental Program for Phase 2, 6.5SLW Concrete

Thickness[a] (in.)	Storage Environment[b] (% RH)	No. of Loaded Specimens at Stress–Strength Ratio of—		No. of Nonloaded (Shrinkage) Specimens
		0.50	0.25	
1	25	3	3	6
1	50	3	3	4
1	100	1	1	3
2	25	3	3	6
2	50	3	3	4
2	100	1	1	5
4	25	3	3	4
4	50	1	1	1
4	100	1	1	1

[a] All specimens were prisms with a width of 5 inches and a length of 12 inches; the variable was thickness.

[b] Temperature of all environments was 73°F; specimens were loaded (or installed) after 14 days of curing in 100% RH.

Table 4. Creep-Plus-Shrinkage, Shrinkage, and Creep for 6.5SLW Concrete

Parameter	Stress–Strength Ratio	Storage Environment (% RH)	Strain Values[a] (μin./in.) for Specimens Loaded—							
			7 Days	14 Days	21 Days	28 Days	56 Days	91 Days	175 Days	365 Days
1-Inch-Thick Specimens										
Creep-Plus-Shrinkage	0.50	25	1,615	2,110	2,330	2,410	2,560	2,650	2,790	2,885
		50	1,305	1,570	1,710	1,805	2,005	2,125	2,275	2,410
		100	495	580	635	675	795	880	1,000	1,090
	0.25	25	1,030	1,305	1,445	1,525	1,610	1,680	1,740	1,790
		50	765	960	1,055	1,110	1,210	1,280	1,385	1,460
		100	215	290	330	365	450	520	630	695
Shrinkage[b]	0.00	25	600	715	770	795	845	885	940	990
		50	385	445	475	495	535	580	645	700
		100	-30	-35	-40	-45	-55	-70	-75	-85
Creep[c]	0.50	25	1,015	1,395	1,560	1,615	1,715	1,765	1,850	1,895
		50	920	1,125	1,235	1,310	1,470	1,545	1,630	1,710
		100	525	615	675	720	850	950	1,075	1,175
	0.25	25	430	590	675	730	765	795	800	800
		50	380	515	580	615	675	700	740	760
		100	245	325	370	410	505	590	705	780
2-Inch-Thick Specimens										
Creep-Plus-Shrinkage	0.50	25	1,125	1,550	1,830	2,000	2,360	2,550	2,735	2,850
		50	1,000	1,375	1,605	1,765	2,130	2,315	2,530	2,685
		100	340	410	465	510	640	750	880	965
	0.25	25	615	890	1,060	1,165	1,375	1,495	1,625	1,710
		50	525	765	910	1,005	1,220	1,345	1,500	1,625
		100	185	230	255	280	330	350	345	340
Shrinkage[b]	0.00	25	315	485	590	655	750	800	855	895
		50	210	375	470	530	665	740	790	825
		100	-45	-55	-65	-70	-85	-100	-120	-135
Creep[c]	0.50	25	810	1,065	1,240	1,345	1,610	1,750	1,880	1,955
		50	790	1,000	1,135	1,235	1,465	1,575	1,740	1,860
		100	385	465	530	580	725	850	1,000	1,100
	0.25	25	300	405	470	510	625	695	770	815
		50	315	390	440	475	555	605	710	810
		100	230	285	320	350	415	450	465	475

continued

Table 4. Continued

Parameter	Stress–Strength Ratio	Storage Environment (% RH)	Strain Values[a] (μin./in.) for Specimens Loaded—							
			7 Days	14 Days	21 Days	28 Days	56 Days	91 Days	175 Days	365 Days
4-Inch-Thick Specimens										
Creep-Plus-Shrinkage	0.50	25	770	1,055	1,250	1,395	1,765	2,010	2,285	2,455
		50	670	910	1,090	1,225	1,585	1,835	2,130	2,290
		100	520	635	710	770	935	1,045	1,140	1,190
		25	400	575	695	795	1,055	1,255	1,490	1,635
		50	405	565	685	775	1,010	1,165	1,365	1,515
		100	240	295	340	375	495	595	660	625
Shrinkage[b]	0.00	25	145	230	300	360	520	615	710	800
		50	85	155	210	255	390	495	645	725
		100	-15	-15	-20	-25	-35	-45	-70	-95
Creep[c]	0.50	25	625	825	950	1,035	1,245	1,395	1,575	1,655
		50	585	755	880	970	1,195	1,340	1,485	1,565
		100	535	650	730	795	970	1,090	1,210	1,285
	0.25	25	255	345	395	435	535	640	780	835
		50	320	410	475	520	620	670	720	790
		100	255	310	360	400	530	640	730	720

[a] When multiple specimens were tested, value represents average.

[b] Negative shrinkage is swellage.

[c] Creep was obtained by subtracting shrinkage from creep-plus-shrinkage.

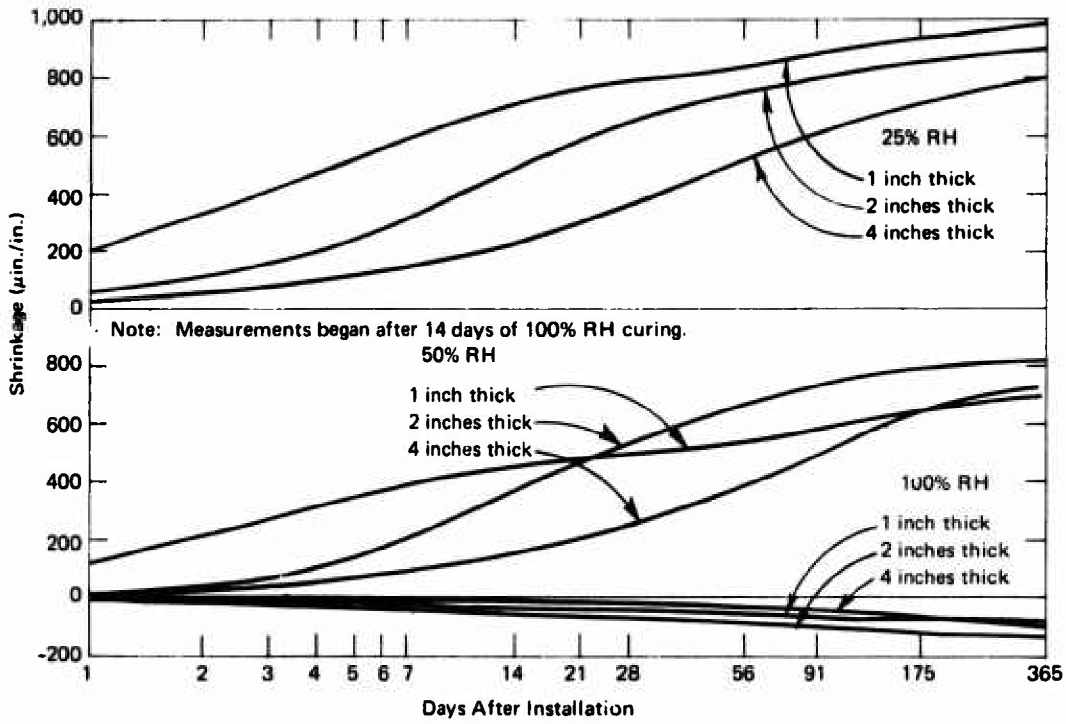


Figure 14. Effects of specimen thickness on shrinkage, 6.5SLW concrete.

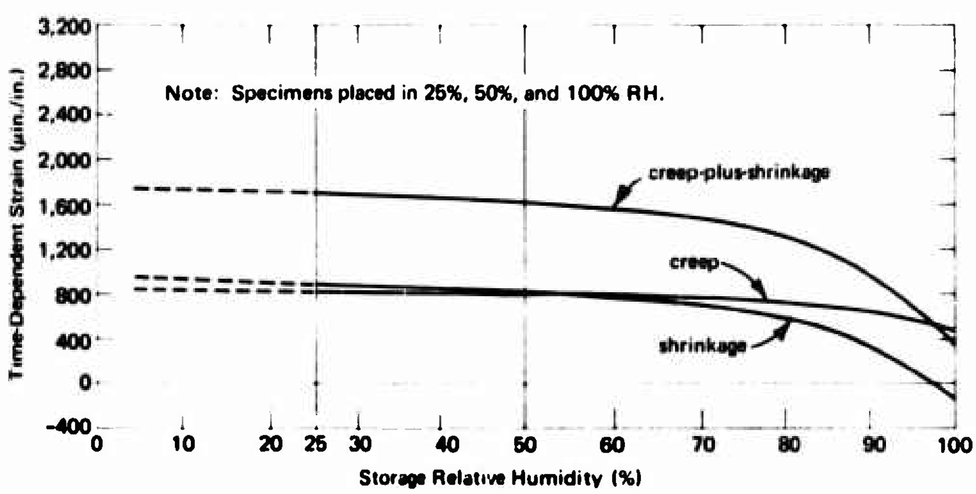


Figure 15. Effects of humidity on 6.5SLW concrete specimens 2 inches thick loaded at $0.25 f_c'$ for 365 days.

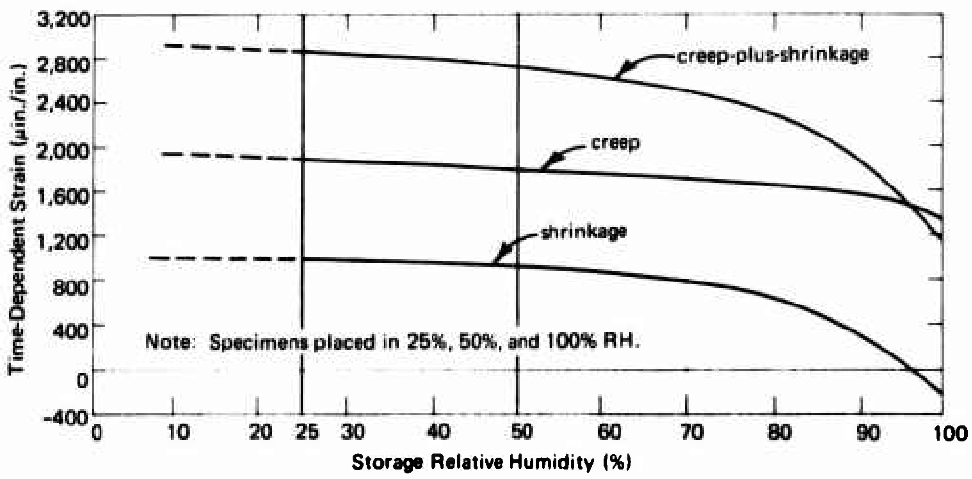
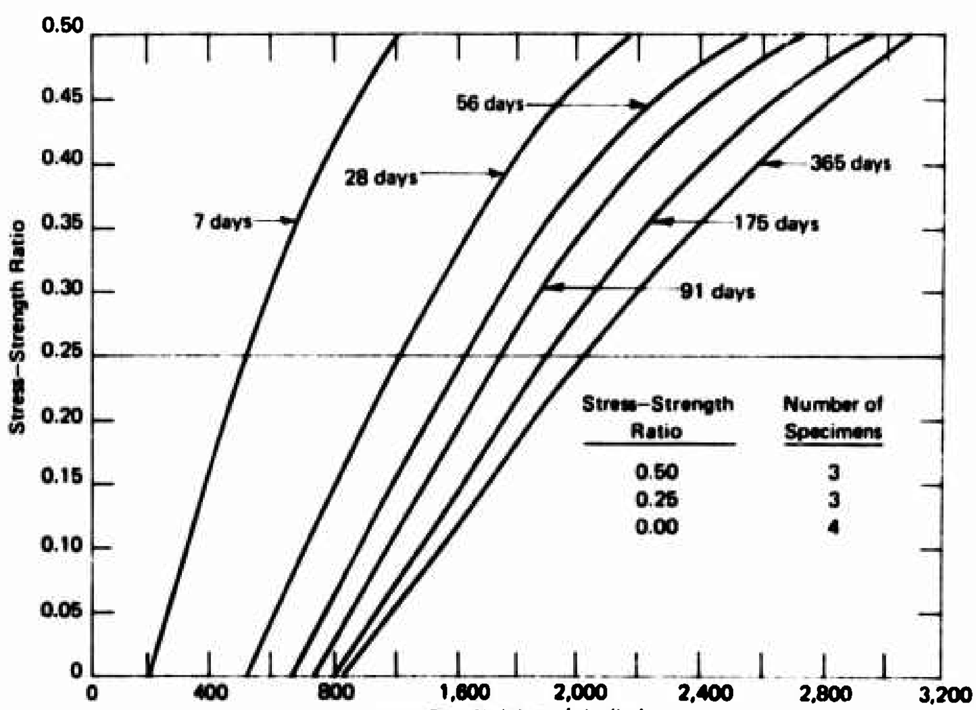
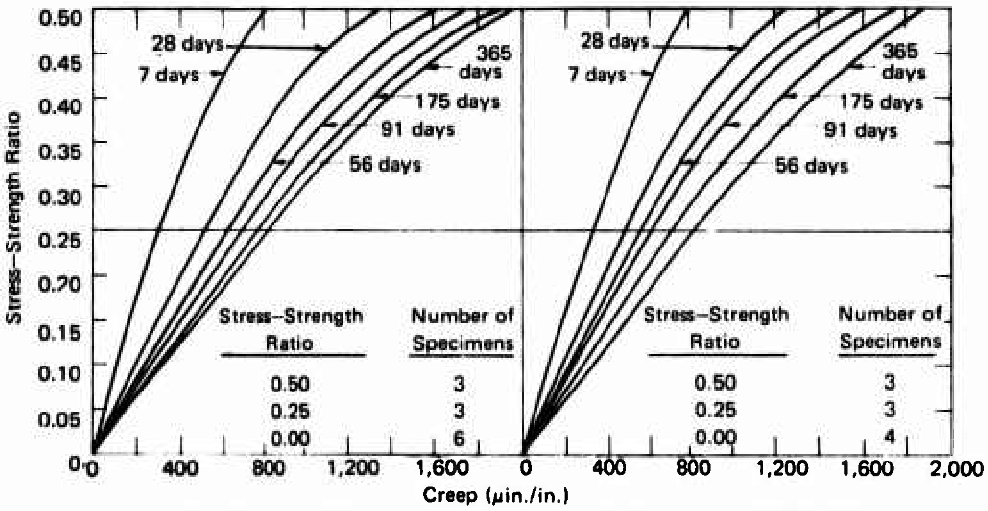


Figure 16. Effects of humidity on 6.5SLW concrete 2 inches thick loaded at $0.50 f_c'$ for 365 days.



Notes: 1. Specimens loaded after 14 days of 100% RH curing.
2. Specimens loaded at $0.50 f_c'$ and $0.25 f_c'$.

Figure 17. Stress versus creep-plus-shrinkage for 6.5SLW concrete specimens 2 inches thick in 50% RH.



(a) Specimens in 25% RH. (b) Specimens in 50% RH.

Note: Specimens loaded after 14 days of 100% RH curing.

Figure 18. Stress versus creep for 6.5SLW concrete specimens 2 inches thick in 50% RH.

7LW All-Lightweight Concrete. The experimental program for 7LW all-lightweight concrete is shown in Table 5. Creep-plus-shrinkage, shrinkage, and creep are presented in Table 6. Curves for creep-plus-shrinkage and shrinkage for specimens 1 inch thick in 25% RH are shown in Figure 19. These curves show quite vividly an interesting phenomenon of lightweight concrete. As stated previously with regard to the sand–lightweight concrete, the expanded shale aggregate gives up at least some of the water it absorbs. In the case of the all-lightweight concrete, the sand is also lightweight expanded shale. The lightweight sand, which absorbs about half again more water than does the coarse, also gives up its absorbed water as the hydrodynamic and vapor pressure laws dictate. In the all-lightweight concrete, then, considerably more water is entrapped in the interior in the form of absorbed water. The effects of the water coming from the aggregate are clearly visible in the curves of Figure 19. The rate of shrinkage is highest between 7 and 14 days. The shrinkage rate then decreases rather rapidly until about 56 days due to the swellage caused by the water from the aggregate, resulting in a net decreased rate of shrinkage. After 56 days, the water which had been absorbed in the aggregate became affected by the high evaporative forces in 25% RH, and the shrinkage rate began to increase. It should be noted, however, that the shrinkage rate close to the end of the study (365 days) was decreasing again.

Table 5. Experimental Program for Phase 2, 7LW All-Lightweight Concrete

Thickness[a] (in.)	Storage Environment[b] (% RH)	No. of Loaded Specimens at Stress–Strength Ratio of—		No. of Nonloaded (Shrinkage) Specimens
		0.50	0.25	
1	25	3	3	4
1	50	3	3	5
1	100	1	1	4
2	25	3	3	4
2	50	2	3	8
2	100	1	1	3
4	25	1	1	1
4	50	1	1	1
4	100	2	1	2

[a] All specimens were prisms with a width of 5 inches and a length of 12 inches; the variable was thickness.

[b] Temperature of all environments was 73°F; specimens were loaded (or installed) after 14 days of curing in 100% RH.

The creep-plus-shrinkage curves also show the influence of the absorbed water in the aggregate. The time in days at which the effect of the absorbed water became apparent is a little later in the curve for $0.25 f'_c$ than in the shrinkage curve and still later in the curve for $0.50 f'_c$. The magnitudes of the strains involved account for the apparent delay in the loaded specimens. The absorbed water causes a certain swellage (negative strain) in the concrete; the effects of this negative strain are more easily detectable in a specimen in which the magnitude of the compressive strain is not great. The net effect in all cases is that the lightweight concrete shrinks and creeps, in a given environment, less than might otherwise be expected. Another contributing factor to lower time-dependent strains than expected is that the absorbed water extracted from the aggregate is available, for a time, to react with any unhydrated cement which may be available. Any additional hydration would strengthen the concrete and result in decreased rates of creep and shrinkage from that time.

Table 6. Creep-Plus-Shrinkage, Shrinkage, and Creep for 7LW Concrete

Parameter	Stress–Strength Ratio	Storage Environment (% RH)	Strain Values[a] (μin./in.) for Specimens Loaded—							
			7 Days	14 Days	21 Days	28 Days	56 Days	91 Days	175 Days	365 Days
1-Inch-Thick Specimens										
Creep-Plus-Shrinkage	0.50	25	1,185	1,625	1,855	1,975	2,170	2,295	2,460	2,600
		50	915	1,215	1,375	1,470	1,650	1,765	1,915	2,060
		100	270	330	370	405	500	560	615	650
	0.25	25	685	990	1,135	1,225	1,330	1,395	1,500	1,580
		50	625	860	970	1,040	1,165	1,235	1,320	1,410
		100	180	220	250	265	295	310	325	295
Shrinkage[b]	0.00	25	350	585	665	705	780	845	935	1,015
		50	290	440	505	535	590	620	645	670
		100	-10	-15	-25	-30	-50	-75	-120	-200
Creep[c]	0.50	25	835	1,040	1,190	1,270	1,390	1,450	1,525	1,585
		50	625	775	870	935	1,060	1,145	1,270	1,390
		100	280	345	395	435	550	635	735	850
	0.25	25	335	405	470	520	550	550	565	565
		50	335	420	465	505	575	615	675	740
		100	190	235	275	295	345	385	445	495
2-Inch-Thick Specimens										
Creep-Plus-Shrinkage	0.50	25	690	940	1,155	1,330	1,720	1,970	2,255	2,460
		50	675	925	1,085	1,205	1,500	1,690	1,910	2,065
		100	430	495	530	555	615	665	725	775
	0.25	25	420	605	750	860	1,165	1,390	1,595	1,690
		50	390	575	705	805	1,025	1,160	1,300	1,385
		100	105	130	150	160	195	220	255	250
Shrinkage[b]	0.00	25	115	220	320	400	645	795	905	965
		50	160	270	350	410	565	635	705	755
		100	-25	-35	-40	-50	-80	-105	-150	-180
Creep[c]	0.50	25	575	720	835	930	1,075	1,175	1,350	1,495
		50	515	655	735	795	935	1,055	1,205	1,310
		100	455	530	570	605	695	770	875	955
	0.25	25	305	385	430	460	520	595	690	725
		50	230	305	355	395	460	525	595	630
		100	130	155	190	210	275	325	405	430

continued

Table 6. Continued

Parameter	Stress–Strength Ratio	Storage Environment (% RH)	Strain Values[a] (μin./in.) for Specimens Loaded—							
			7 Days	14 Days	21 Days	28 Days	56 Days	91 Days	175 Days	365 Days
4-Inch-Thick Specimens										
Creep-Plus-Shrinkage	0.50	25	340	495	605	695	930	1,140	1,435	1,605
		50	530	695	805	895	1,145	1,355	1,645	1,770
		100	385	470	510	545	620	670	735	790
	0.25	25	170	265	340	405	610	785	1,030	1,180
		50	160	245	315	375	550	685	855	960
		100	150	185	205	215	250	260	225	215
Shrinkage[b]	0.00	25	45	105	150	190	325	480	675	765
		50	20	40	60	80	145	230	390	450
		100	-40	-50	-55	-65	-80	-95	-130	-165
Creep[c]	0.50	25	295	390	455	505	605	660	760	840
		50	510	655	745	815	1,000	1,125	1,255	1,320
		100	425	520	565	610	700	765	865	955
	0.25	25	125	160	190	215	285	305	355	415
		50	140	205	255	295	405	455	465	510
		100	190	235	260	280	330	355	355	380

[a] When multiple specimens were tested, value represents average.

[b] Negative shrinkage is swellage.

[c] Creep was obtained by subtracting shrinkage from creep-plus-shrinkage.

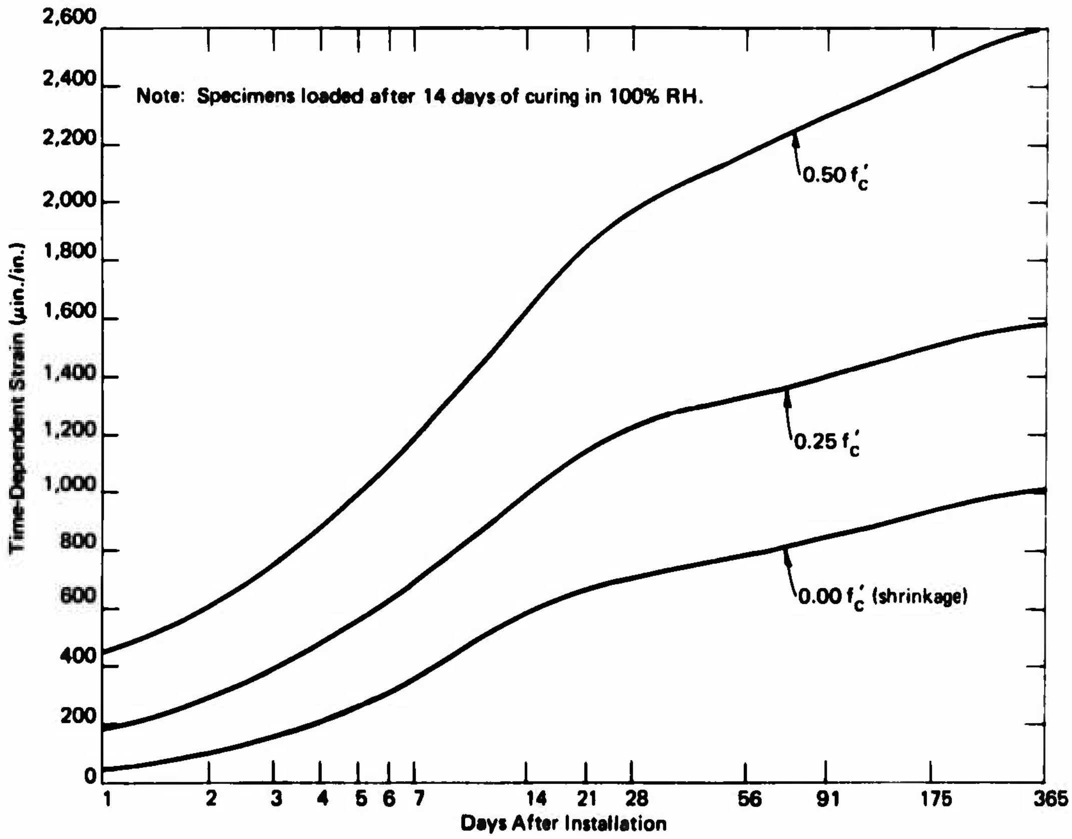


Figure 19. Creep-plus-shrinkage and shrinkage of 7LW concrete specimens 1 inch thick in 25% RH.

The effects of thickness on creep-plus-shrinkage of specimens loaded at 0.50 f_c' in 50% RH are shown in Figure 20. At 365 days, creep-plus-shrinkage is almost identical for 1- and 2-inch-thick specimens, although the slope of the 1-inch curve indicates that it might continue to increase beyond 365 days. As stated before, the difference in percentage of reinforcement most likely accounts for the small difference between 1- and 2-inch-thick specimens.

The effects of humidity on creep-plus-shrinkage, shrinkage, and creep are shown in Figures 21 and 22 for specimens 2 inches thick loaded at 0.25 f_c' and 0.50 f_c', respectively. Similar curves can be drawn for specimens 1 inch and 4 inches thick by using data in Table 6. From these curves the time-dependent strains can be determined for any humidity between 25% RH and 100% RH.

Figure 23 shows the relationships between stress—strength ratio and creep-plus-shrinkage for specimens 2 inches thick in 50% RH. These relationships come much closer to being linear for this concrete than for 8.25NW or 6.5SLW concrete. After 365 days, however, there is still definite nonlinearity above a stress—strength ratio of about 0.30. The relationships between stress—strength ratio and creep are shown in Figure 24. Some of the curves approach a straight line but, after 365 days, the relationship is curvilinear above a stress–strength ratio of 0.30. With curves such as those shown in Figures 23 and 24, creep-plus-shrinkage and creep can be obtained for any stress–strength ratio between 0.00 and 0.50.

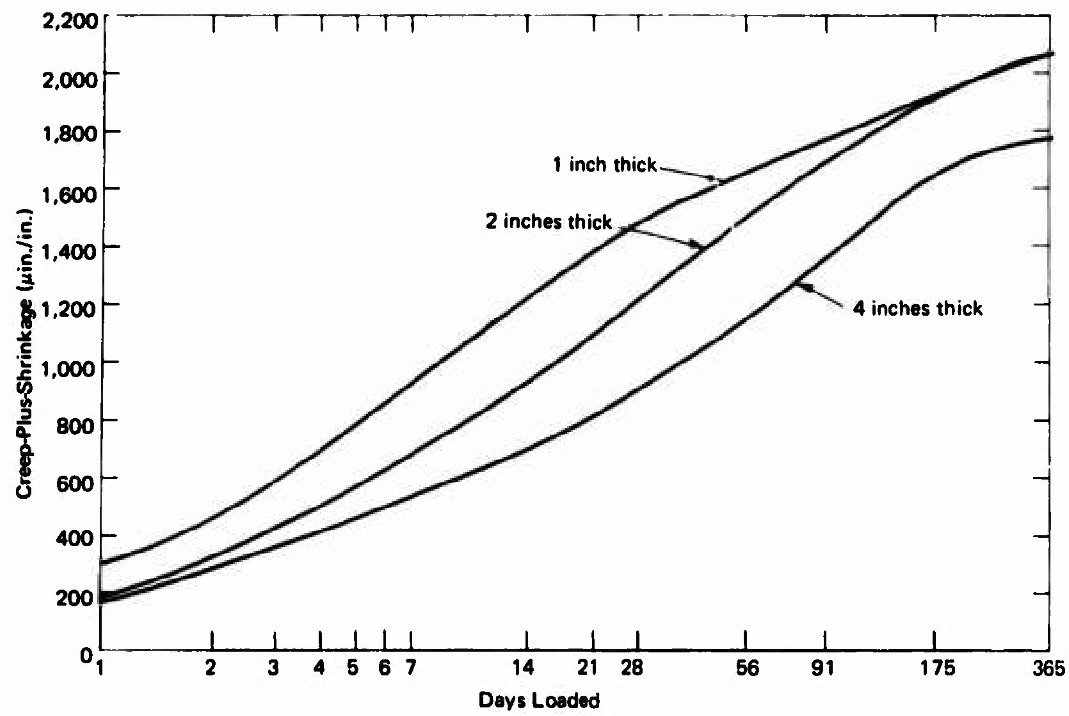


Figure 20. Creep-plus-shrinkage of 7LW concrete specimens loaded at $0.50 f_c'$ in 50% RH.

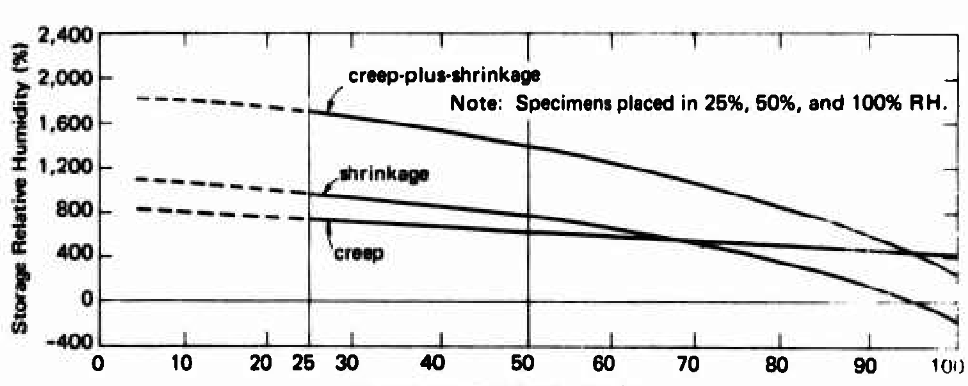


Figure 21. Effects of humidity on 7LW concrete specimens 2 inches thick loaded at $0.25 f_c'$ for 365 days.

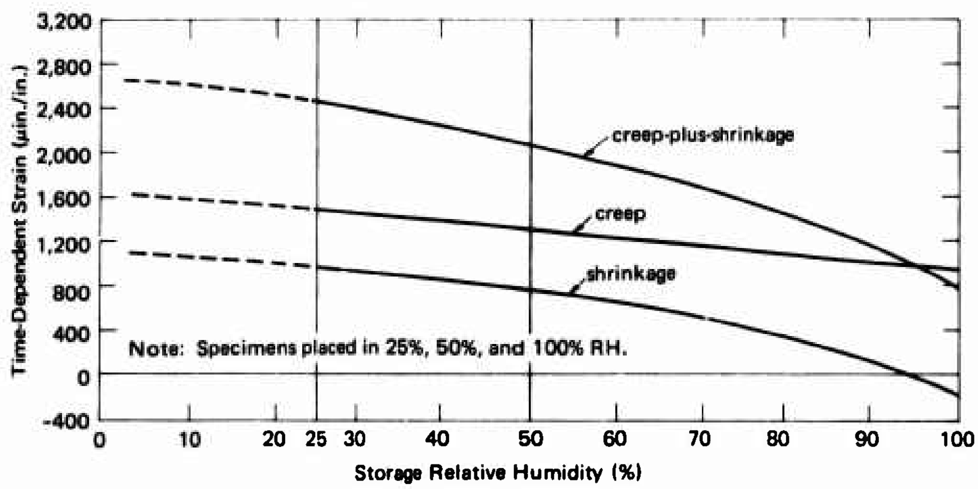


Figure 22. Effects of humidity on 7LW concrete specimens 2 inches thick loaded at $0.50 f_c'$ for 365 days.

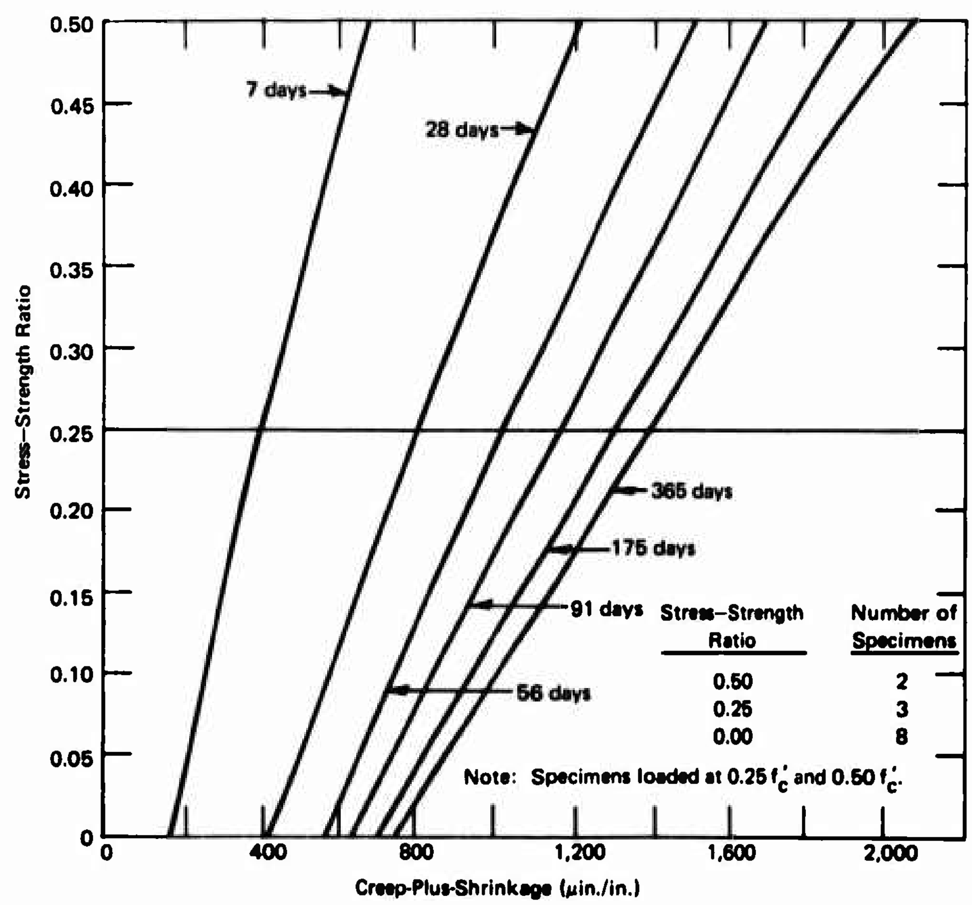
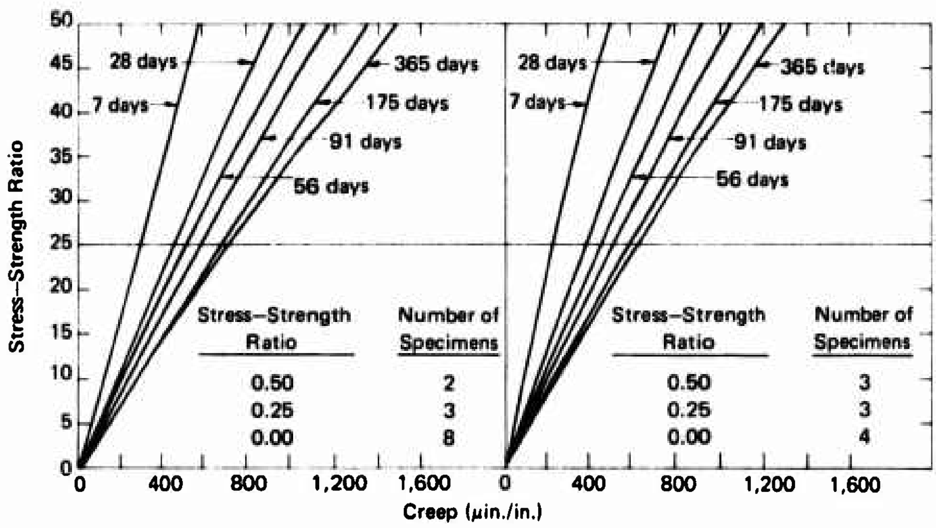


Figure 23. Stress versus creep-plus-shrinkage for 7LW concrete specimens 2 inches thick in 50% RH.



(a) Specimens in 25% RH. (b) Specimens in 50% RH.

Figure 24. Stress versus creep for 7LW concrete specimens 2 inches thick in 25% RH.

Phase 3—Miscellaneous Tests

Effects of Reinforcing on Time-Dependent Strains. Figure 25 shows the effects of reinforcing on shrinkage of 8.25NW concrete specimens 1 inch thick in 25% RH. There is a slight overlap between 7 and 12 days, but generally speaking, the shrinkage of the unreinforced specimens exceeded that of the reinforced specimens by 10.3% (1,230 over 1,115 μin./in.), but the slope of the curves reveals that the shrinkage of the unreinforced specimens would increase somewhat more after 365 days.

Creep-plus-shrinkage curves for reinforced and unreinforced specimens 1 inch thick in 70% RH are shown in Figure 26. At 91 days the strains of the unreinforced specimens were 4.5% (2,430 over 2,325 μin./in.) and 8.3% (1,440 over 1,330 μin./in.) greater than those of the reinforced specimens for stress–strength ratios of 0.50 and 0.25, respectively. Measurements on unreinforced specimens stopped at 152 days because the 70% RH was changed to 50% RH.

Oxidation of Galvanized Mesh Reinforcement. At the conclusion of the study, some of the specimens were broken to recover the galvanized mesh. The pieces of mesh from each specimen, together with unused identical pieces of mesh, were stripped of zinc by the hydrochloric acid method described in ASTM A-90.[16] The percent oxidation of the zinc coating for each specimen is shown in Table 7. Results for each specimen of the three different concretes are shown in order of descending percentages of oxidation. On the whole, the highest oxidation values are found in specimens of 7LW concrete, somewhat lower in 6.5SLW, and the lowest in 8.25NW. The thicker specimens show greater oxidation. Although there are some inherent variations to any generalized explanation of concrete behavior, the author believes that the results found in Table 7 can be related to the pH of the concrete matrix.

In recent years, considerable attention has been given to research on corrosion of steel in concrete. The pH of freshly mixed concrete is quite high (about 13) and Griffin[17, 18] has stated that if the pH of the hardened concrete remains above 12, there will be no destructive corrosion of embedded steel. He has also shown that if the pH is lowered to about 10 by intrusion of salts or by carbonation, the conditions become ideal for steel corrosion. Steel with a zinc coating (galvanized) presents a somewhat different situation. The zinc coating is amphoteric; that is, it is highly susceptible to oxidation, either to a zincate by a highly alkaline (high pH) solution or to a zinc salt by a highly acidic (low pH) solution, and is moderately susceptible to oxidation at any pH. It is least susceptible at a pH of about 9.

Table 7. Oxidation of Zinc Coating From Mesh Reinforcement

Specimen	Specimen Thickness (in.)	Storage Environment (% RH)	Stress–Strength Ratio[a]	Oxidation of Zinc Coating (%)
8.25NW concrete	2	70	0.0	23
	1	70	0.0	8
6.5SLW concrete	4	25	0.25	25
	4	25	0.50	25
	2	25	0.50	21
	2	25	0.25	17
	1	25	0.25	2
7LW all-light-weight concrete	2	50	0.50	32
	2	50	0.25	28
	2	50	0.25	24
	1	50	0.50	2

[a] A stress–strength ratio of 0.0 indicates a shrinkage specimen.

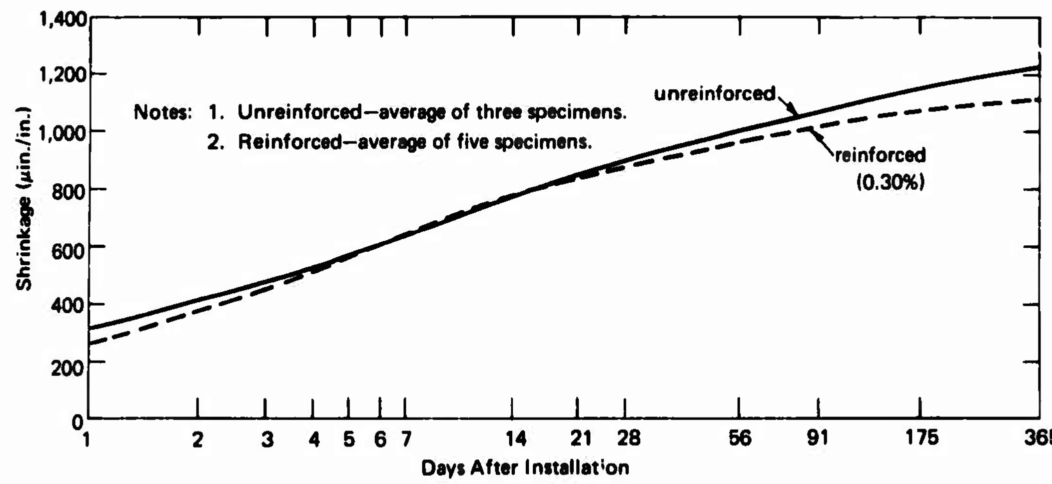


Figure 25. Shrinkage of unreinforced and reinforced 8.25NW concrete specimens 1 inch thick in 70% RH.

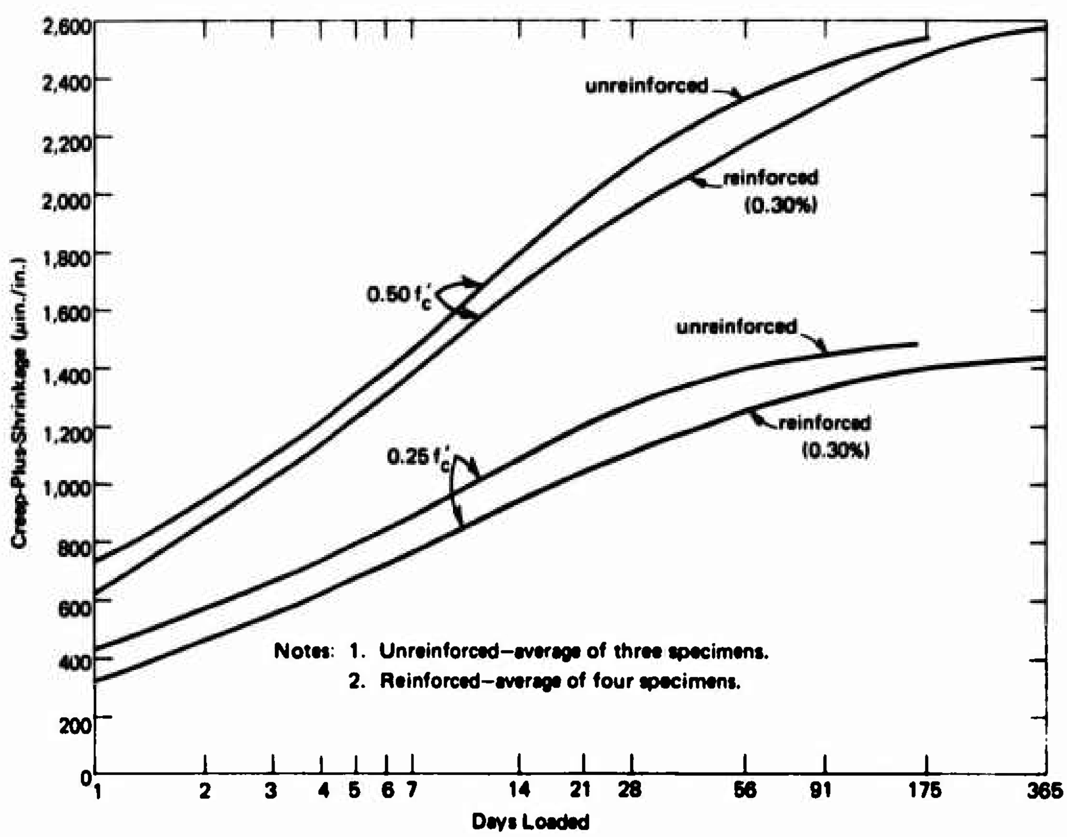


Figure 26. Creep-plus-shrinkage of unreinforced and reinforced 8.25NW concrete specimens 1 inch thick.

In this study there were no percolating salts to lower the pH of the concrete from its originally high value of 13. Carbonation, which is the conversion of calcium hydroxide or free lime [$Ca(OH)_2$] to calcium carbonate ($CaCO_3$) and free water by the carbon dioxide in the air has been shown to occur at all humidities, with the rate being highest in a humidity close to 50% RH. The formation of carbonic acid (H_2CO_3) during carbonation would lower the pH, but carbonation begins at the outer concrete surface and works its way inward quite slowly. Thus, in a given period, its effects would be felt soonest in a thinner specimen. This is borne out in the data in Table 7, which shows the least oxidation in the 1-inch-thick specimens. The higher rate of oxidation in the two lightweight concretes can be explained in terms of the water absorbed by the expanded-shale aggregate. Shortly after being introduced into the concrete batch, the mixing water became highly alkaline and it was in this condition when it was absorbed by the aggregate. Later some of this highly alkaline water was drawn back into the concrete and thus tended to maintain a high pH. The 7LW all-lightweight concrete had the highest zinc oxidation rates because more of the highly alkaline water was available for reentry into the concrete, as mentioned previously in this report.

DISCUSSION OF TEST RESULTS

Time-dependent strains for all concretes used in this study are compared in Table 8. The values at 50% RH for 8.25NW concrete and the values at 70% RH for 6.5SLW concrete and for 7LW all-lightweight concrete were interpolated from curves similar to those shown in Figure 10.

With the exception of data in 100% RH, creep-plus-shrinkage values for specimens 1 inch thick are highest for 8.25NW, somewhat less for 6.5SLW, and lowest for 7LW concrete. Except for data in 25% RH, shrinkage values show the same relationship. Creep values for specimens 1 inch thick seem to break the trend somewhat in 25% RH for both stress–strength ratios (0.25 and 0.50); creep is highest in 6.5SLW concrete. The same observation can be made for creep in 50% RH at a stress–strength ratio of 0.25 and in 100% RH at both stress–strength ratios. Relationships in 70% RH show creep at $0.50 f'_c$ to be highest in 8.25NW concrete, but creep at $0.25 f'_c$ is highest in 7LW concrete. Generally speaking, the trend in the drying humidities seems to be that time-dependent strains were higher in 8.25NW than in 6.5SLW and lowest in 7LW concrete. The same observations, with variations here and there, can be made for specimens 2 inches thick from Table 8. The lack of multiple specimens 4 inches thick for lightweight concretes 6.5SLW and 7LW precluded similar meaningful comparisons. Reichard,[19] in an extensive study of lightweight and normal-weight concretes, found relationships similar to those described above.

Table 8. Comparisons of Time-Dependent Strains for All Concretes

Parameter	Stress–Strength Ratio	Storage Environment (% RH)	Strain Values (μ in./in.) at 365 Days for—		
			8.25NW Concrete	6.5SLW Concrete	7LW Concrete
1-Inch-Thick Specimens					
Creep-Plus-Shrinkage	0.50	25	2,865	2,885	2,600
		50	2,760[a]	2,410	2,060
		70	2,580	1,980[b]	1,570[b]
		100	865	1,090	650
	0.25	25	1,865	1,790	1,580
		50	1,710[a]	1,460	1,410
		70	1,440	1,160[b]	1,145[b]
		100	360	695	295
Shrinkage[c]	0.00	25	1,115	990	1,015
		50	1,035[a]	700	670
		70	885	430[b]	380[b]
		100	-150	-85	-200
Creep	0.50	25	1,750	1,895	1,585
		50	1,725	1,710	1,390
		70	1,695	1,550	1,190
		100	1,015	1,175	850
	0.25	25	750	800	565
		50	675	760	740
		70	555	730	765
		100	510	780	495
2-Inch-Thick Specimens					
Creep-Plus-Shrinkage	0.50	25	2,855	2,850	2,460
		50	2,715[a]	2,685	2,065
		70	2,490	2,420[b]	1,680[b]
		100	1,135	965	775
	0.25	25	1,855	1,710	1,690
		50	1,685[a]	1,625	1,385
		70	2,490	2,420[b]	1,065[b]
		100	1,135	965	775
Shrinkage[c]	0.00	25	975	895	[illegible]
		50	925[a]	825	[illegible]
		70	785	695[b]	[illegible][b]
		100	-220	-135	[illegible]
Creep	0.50	25	1,880	1,955	1,495
		50	1,790	1,860	1,310
		70	1,705	1,725	1,160
		100	1,355	1,100	955

continued

Table 8. Continued

Parameter	Stress–Strength Ratio	Storage Environment (% RH)	Strain Values (μin./in.) at 365 Days for— 8.25NW Concrete	6.5SLW Concrete	7LW Concrete
Creep	0.25	25	880	815	725
		50	760	810	630
		70	655	770	545
		100	675	475	430
4-Inch-Thick Specimens					
Creep-Plus-Shrinkage	0.50	25	2,765	2,455	1,605
		50	2,600[a]	2,290	1,525[d]
		70	2,345	2,090[b]	1,400[d]
		100	1,160	1,190	790
	0.25	25	1,730	1,635	1,180
		50	1,600[a]	1,515	960
		70	1,365	1,335[b]	730
		100	500	625	215
Shrinkage[c]	0.00	25	890	800	765
		50	810[a]	725	505[d]
		70	695	595[b]	280[d]
		100	-145	-95	-165
Creep	0.50	25	1,875	1,655	840
		50	1,790	1,565	1,020[d]
		70	1,650	1,495	1,120[d]
		100	1,305	1,285	955
	0.25	25	840	835	415
		50	790	790	455[d]
		70	670	740	450[d]
		100	645	720	380

[a] Time-dependent strain data for 8.25NW concrete at 50% RH were interpolated from curves such as in Figures 10 and 11.

[b] Time-dependent strain data for 6.5SLW and 7LW concretes at 70% RH were interpolated from curves such as in Figures 13, 14, 19, and 20.

[c] Negative shrinkage is swellage.

[d] These values for specimens 4 inches thick of 7LW concrete were adjusted slightly from measured data to fit curves such as those shown in Figure 20.

Creep and creep-plus-shrinkage coefficients for 365 days of loading are shown in Tables 9, 10, and 11 for 8.25NW, 6.5SLW, and 7LW concretes, respectively. The creep coefficient is defined as creep strain divided by initial strain. Values shown for initial loading strains are averages for the specimens loaded. Use of a creep coefficient eliminates necessity for separate consideration of stress level or of modulus of elasticity, since the initial strain reflects both of these factors. In general, creep coefficients were highest in 8.25NW, slightly lower in 6.5SLW, and lowest in 7LW concrete.

The use of creep coefficients by designers to compute expected creep of structures is predicated upon the assumption that there is a linear relationship between time-dependent strain and stress—strength ratio.[20,21] If this assumption of linearity were true for NCEL data reported herein, the creep coefficients shown in Tables 9, 10, and 11 would be equal for stress—strength ratios of 0.25 and 0.50 at each specimen thickness. In addition to the nonlinearity observed in this and previous NCEL work,[4-6] many other researchers have also found this relationship to be nonlinear. However, designers have chosen to use mathematical equations based on assumption of a linear relationship to facilitate their computations.

APPLICATIONS TO DESIGN

Culminating several years of experimental and analytical efforts by its members, Subcommittee II of Technical Committee 209 (Creep and Shrinkage in Concrete) of the American Concrete Institute (ACI) has prepared a report in which methods are presented for applying creep coefficient and shrinkage factors to the design of structural concrete elements of normal-weight, sand—lightweight, and all-lightweight concrete.[22] These same methods, for the most part, are also being considered by ACI Committee 318 (Building Code) for inclusion in the 1971 ACI Building Code. The following equations and most of the correction curves for creep coefficients and shrinkage presented herein are taken from the ACI Committee 209 report[22] and from Branson et al.[23] Some of the correction curves were extended with test data obtained on this study of thin-shell reinforced concrete. The correction curves for unit weight are based on data reported herein.

Creep and Shrinkage Equations

The following equations are recommended for predicting creep (C) and shrinkage (sh) of concrete:[22]

$$C_t = \frac{t^c}{d + t^e} C_u \qquad (1)$$

$$(\epsilon_{sh})_t = \frac{t^e}{f + t^e} (\epsilon_{sh})_u \qquad (2)$$

where C_t = creep coefficient at any time, **t**, after being loaded

C_u = ultimate creep coefficient; creep coefficient = creep strain/initial strain

$(\epsilon_{sh})_t$ = shrinkage strain at any time, **t**

$(\epsilon_{sh})_u$ = ultimate shrinkage strain

c, d, e, f = constants, obtained empirically

When the power of **t** is unity, Equations 1 and 2 resemble the hyperbolic equations of Ross[20] and Lorman.[21] In an analysis of data gathered by many authors, including data for normal weight, sand—lightweight, and all-lightweight concretes, the following ranges were found for the constants and for creep and shrinkage factors for Equations 1 and 2:[22,23]

C_u = 1.30 to 4.15

$(\epsilon_{sh})_u$ = 415 x 10^{-6} to 1,070 x 10^{-6} in./in.

C = 0.40 to 0.80

d = 6 to 30

e = 0.90 to 1.10

f = 20 to 130

From all the data studied, so called "standard conditions" were established from which adjustments can be made in creep coefficients and shrinkage values to fit any given set of actual conditions. The "standard conditions" adopted for the ACI Committee 209 report were as follows:

Relative humidity = 40%

Thickness = 6 inches, minimum

Loading age = 7 days

C_u = 2.35 for 20-year period

$(\epsilon_{sh})_u$ = 800 x 10^{-6} in./in. for 20-year period

For these "standard conditions," Equations 1 and 2 become

$$C_t = \frac{t^{0.60}}{10 + t^{0.60}} C_u \tag{3}$$

$$(\epsilon_{sh})_t = \frac{t}{35 + t} (\epsilon_{sh})_u \tag{4}$$

Correction Factors

The correction factors shown below should be applied to the ultimate values for creep and shrinkage. For example, if a correction factor for the creep coefficient is found to be 0.90, the 0.90 should be multiplied by $\mathbf{C_u}$ (or 2.35) to obtain the correct $\mathbf{C_u}$ to use in Equation 3.

Correction Factors for Loading Age. Figure 27 shows the curve of creep and shrinkage correction factors for loading age. For the tests reported in this study, in which specimens were loaded at 14 days, the correction factor is 0.91, or $\mathbf{C_u}$ for this correction is 2.35 x 0.91 = 2.14.

Correction Factors for Humidity. Creep correction factors for humidity are shown in Figure 28. The curve represents ultimate values for 20 years, with the standardized value of 40% RH = 1.00. For a humidity of 60% RH, the $\mathbf{C_u}$ should be multiplied by 0.87 or 2.35 x 0.87 = 2.04.

Shrinkage correction factors for humidity are presented in Figure 29. For shrinkage at 60% RH, the $(\epsilon_{sh})_u$ of 800 x 10^{-6} in./in. should be multiplied by 0.80, resulting in a $(\epsilon_{sh})_u$ of 640 x 10^{-6} in./in. to be used in Equation 4 for computing shrinkage at any age.

Correction Factors for Member Thickness. Figure 30 shows curves of creep correction factors for minimum member thickness. The upper curve is for 20 years, the lower curve for 1 year. The dashed extension of the 1-year curve represents data for 1-inch, 2-inch, and 4-inch thicknesses obtained in the study reported herein. The 20-year curve is converging with the 1-year curve as thickness decreases.

Shrinkage correction factors for the minimum thickness of a member are shown in Figure 31. The upper curve is the 20-year curve, and the lower curve is for 1 year. The dashed extension on the 1-year curve represents data obtained in this study.

Table 9. Creep and Creep-Plus-Shrinkage Coefficients for 8.25NW Concrete

Stress–Strength Ratio	Storage Environment (% RH)	Initial Loading Strain (μin./in.)	Creep at 365 Days		Creep-Plus-Shrinkage at 365 Days	
			Strain (μin./in.)	Coefficient[a]	Strain (μin./in.)	Coefficient[b]
1-Inch-Thick Specimens						
0.50	25	815	1,750	2.15	2,865	3.50
	50[c]	860	1,725	2.00	2,760	3.20
	70	855	1,695	2.00	2,580	3.00
	100	915	1,015	1.10	865	0.95
0.25	25	445	750	1.70	1,865	4.20
	50[c]	415	675	1.65	1,710	4.10
	70	370	555	1.50	1,440	3.90
	100	430	510	1.20	360	0.85
2-Inch-Thick Specimens						
0.50	25	940	1,880	2.00	2,855	3.05
	50[c]	1,010	1,790	1.75	2,715	2.70
	70	1,055	1,705	1.60	2,490	2.35
	100	1,005	1,355	1.35	1,135	1.15
0.25	25	455	880	1.95	1,855	4.10
	50[c]	420	760	1.80	1,685	4.00
	70	400	655	1.65	1,440	3.60
	100	425	675	1.60	455	1.05
4-Inch-Thick Specimens						
0.50	25	1,030	1,875	1.80	2,765	2.70
	50[c]	1,010	1,790	1.77	2,600	2.58
	70	990	1,650	1.65	2,345	2.40
	100	1,015	1,305	1.30	1,160	1.15
0.25	25	430	840	1.95	1,730	4.00
	50[c]	440	790	1.80	1,600	3.64
	70	480	670	1.40	1,365	2.85
	100	430	645	1.50	500	1.15

[a] Creep coefficient = creep strain ÷ initial loading strain.

[b] Creep-plus-shrinkage coefficient = creep-plus-shrinkage strain ÷ initial loading strain.

[c] Time-dependent strains for 50% RH were obtained from curves such as those in Figure 10.

Table 10. Creep and Creep-Plus-Shrinkage Coefficients for 6.5SLW Concrete

Stress–Strength Ratio	Storage Environment (% RH)	Initial Loading Strain (μin./in.)	Creep at 365 Days		Creep-Plus-Shrinkage at 365 Days	
			Strain (μin./in.)	Coefficient[a]	Strain (μin./in.)	Coefficient[b]
1-Inch-Thick Specimens						
0.50	25	1,445	1,895	1.30	2,885	2.00
	50	930	1,710	1.85	2,410	2.60
	70[c]	1,180	1,550	1.30	1,980	1.70
	100	1,170	1,175	1.00	1,090	0.90
0.25	25	760	800	1.05	1,790	2.35
	50	480	760	1.60	1,460	3.05
	70[c]	615	730	1.20	1,160	2.90
	100	600	780	1.30	695	1.15
2-Inch-Thick Specimens						
0.50	25	1,095	1,955	1.80	2,850	2.60
	50	1,110	1,860	1.65	2,685	2.40
	70[c]	1,095	1,725	1.55	2,420	2.20
	100	1,080	1,100	1.00	965	0.90
0.25	25	495	815	1.65	1,710	3.45
	50	545	810	1.50	1,625	3.00
	70[c]	515	770	1.50	1,465	2.85
	100	510	475	1.05	345	0.70
4-Inch-Thick Specimens						
0.50	25	1,200	1,655	1.40	2,455	2.05
	50	1,120	1,565	1.40	2,290	2.05
	70[c]	1,175	1,495	1.25	2,090	1.80
	100	1,210	1,285	1.05	1,190	1.00
0.25	25	515	835	1.60	1,635	3.15
	50	760	790	1.05	1,515	2.00
	70[c]	640	740	1.15	1,355	2.10
	100	650	720	1.10	625	0.95

[a] Creep coefficient = creep strain ÷ initial loading strain.

[b] Creep-plus-shrinkage coefficient = creep-plus-shrinkage strain ÷ initial loading strain.

[c] Time-dependent strains for 70% RH were obtained from curves such as those in Figure 15.

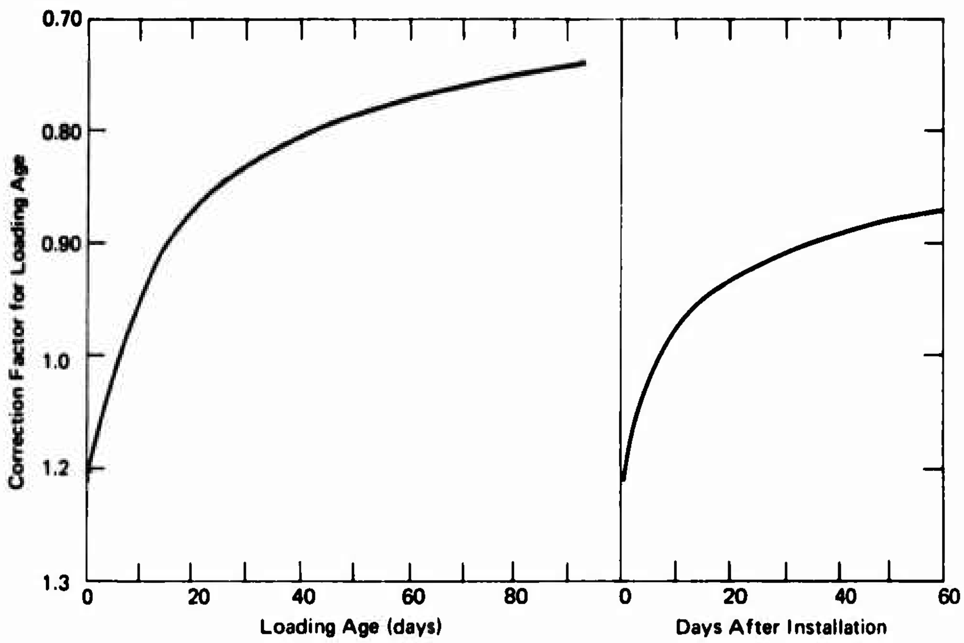
Table 11. Creep and Creep-Plus-Shrinkage Coefficients for 7LW Concrete

Stress–Strength Ratio	Storage Environment (% RH)	Initial Loading Strain (μin./in.)	Creep at 365 Days		Creep-Plus-Shrinkage at 365 Days	
			Strain (μin./in.)	Coefficient[a]	Strain (μin./in.)	Coefficient[b]
1-Inch-Thick Specimens						
0.50	25	1,310	1,585	1.20	2,600	2.00
	50	1,250	1,390	1.10	2,060	1.65
	70[c]	1,325	1,190	0.90	1,145	1.75
	100	1,410	850	0.60	650	0.45
0.25	25	615	565	0.90	1,580	2.55
	50	630	740	1.15	1,410	2.25
	70[c]	650	495	0.75	1,145	1.75
	100	700	495	0.70	295	0.40
2-Inch-Thick Specimens						
0.50	25	1,315	1,495	1.15	2,460	1.85
	50	1,250	1,310	1.05	2,065	2.10
	70[c]	1,330	955	0.70	1,680	1.25
	100	1,420	955	0.65	775	0.55
0.25	25	615	725	1.20	1,690	1.35
	50	590	630	1.05	1,385	2.35
	70[c]	670	430	0.65	1,065	1.60
	100	740	430	0.60	250	0.35
4-Inch-Thick Specimens						
0.50	25	1,270	840	0.65	1,605	1.25
	50	1,210	1,320	1.10	1,770	1.45
	100	1,325	955	0.70	790	0.60
0.25	25	575	415	0.70	1,180	2.05
	50	550	510	0.95	960	1.75
	100	600	380	0.65	215	0.35

[a] Creep coefficient = creep strain ÷ initial loading strain.

[b] Creep-plus-shrinkage coefficient = creep-plus-shrinkage strain ÷ initial loading strain.

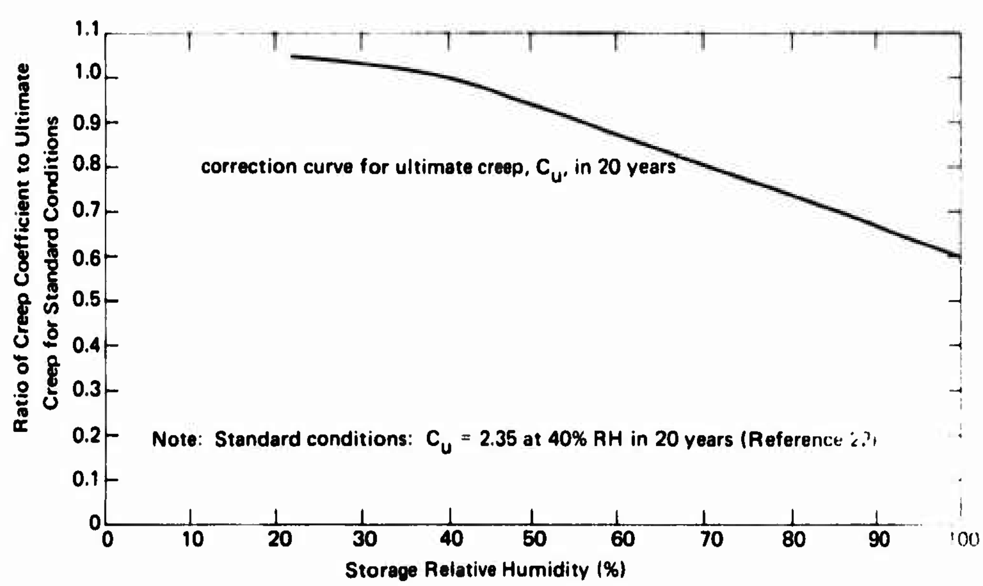
[c] Time-dependent strains for 70% RH were obtained from curves such as those in Figure 21.



(a) Creep correction factors for loading age (References 22, 23).

(b) Shrinkage correction factors for loading age (References 22, 23).

Figure 27. Creep and shrinkage correction factors for loading age.



Note: Standard conditions: C_u = 2.35 at 40% RH in 20 years (Reference 23)

Figure 28. Creep correction factors for humidity.

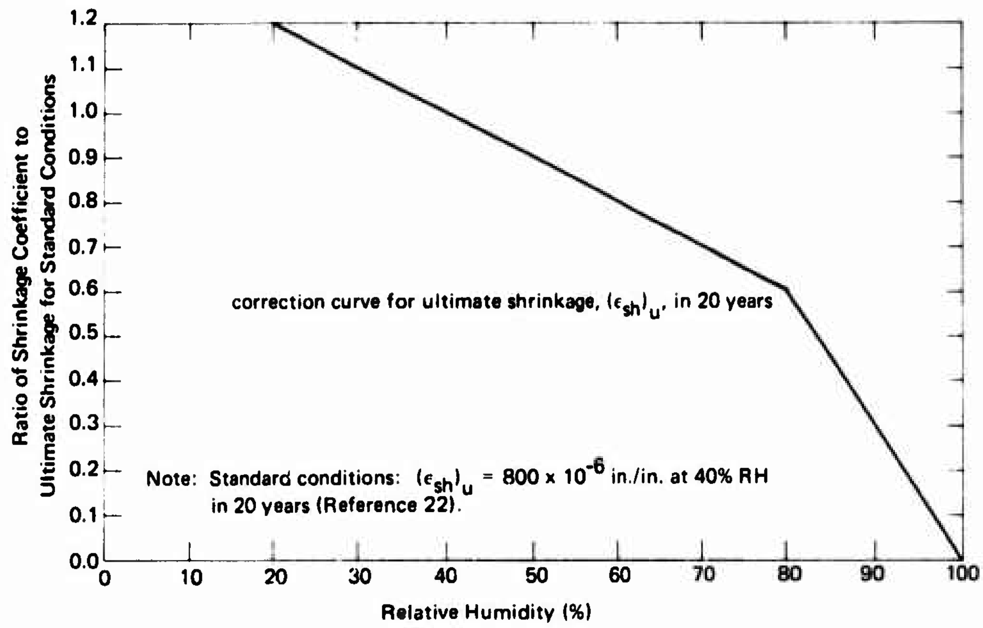


Figure 29. Shrinkage correction factors for humidity.

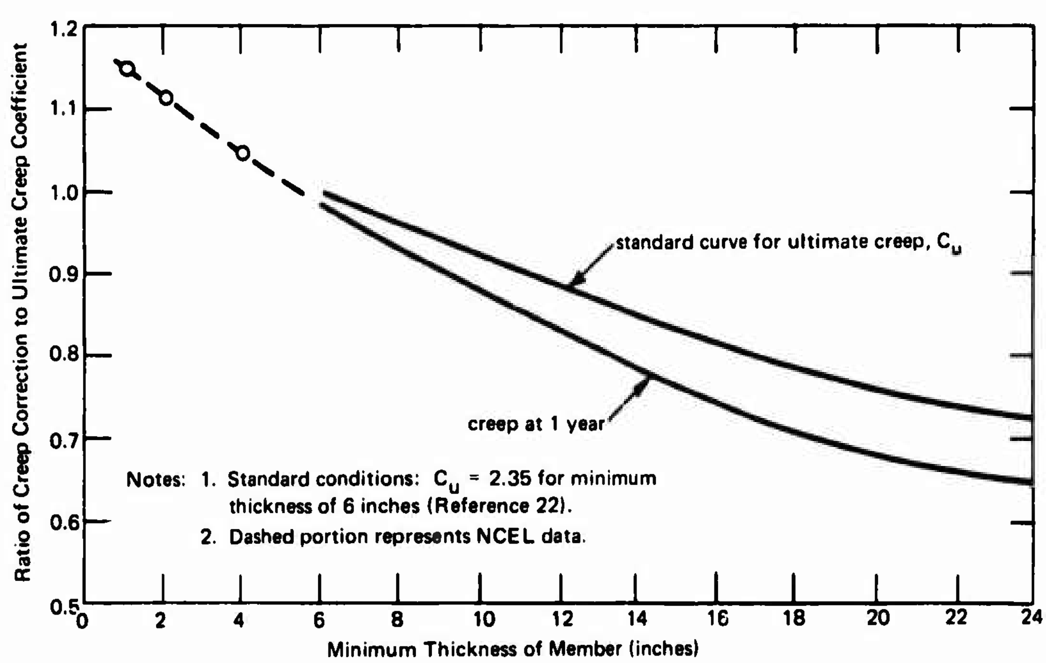


Figure 30. Creep correction factors for minimum thickness of member.

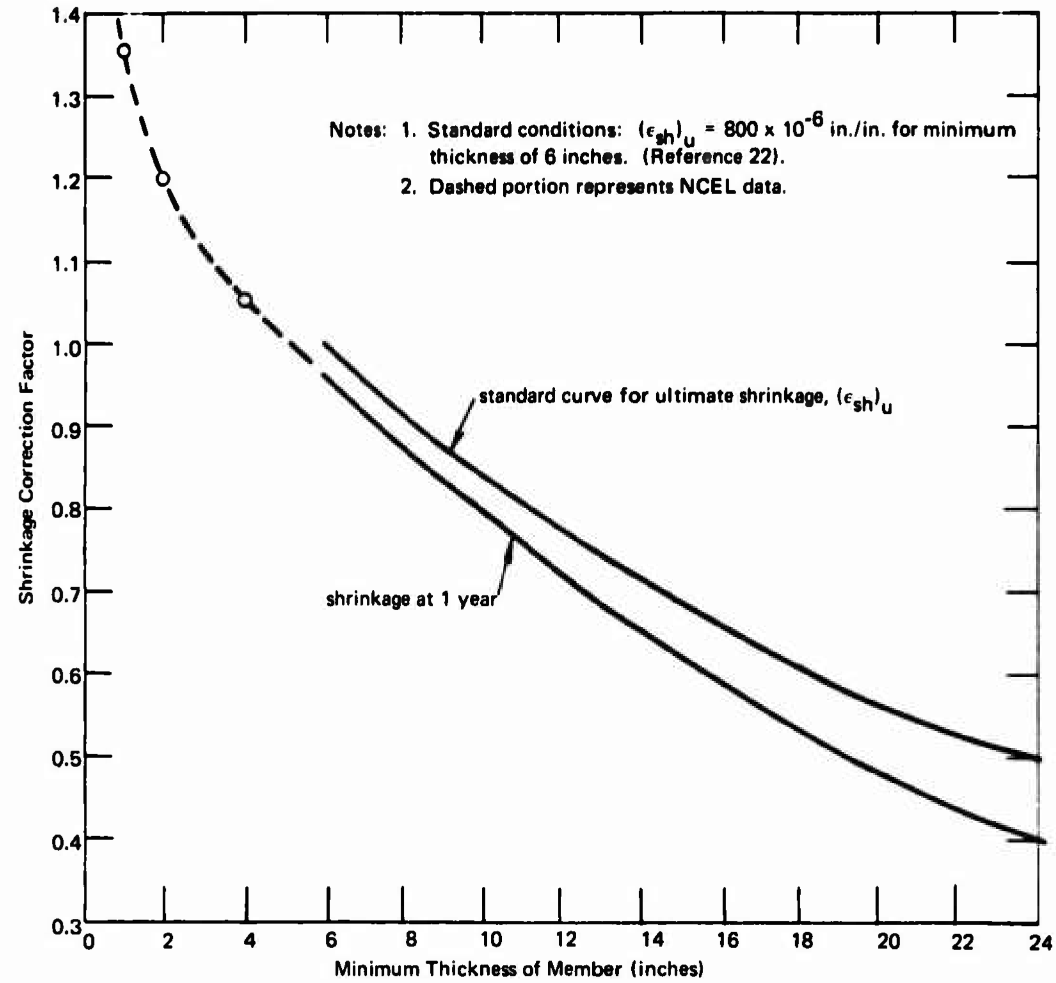


Figure 31. Shrinkage correction factor for minimum thickness of member.

Correction Factors for Unit Weight. As stated above, the equations and correction factors recommended in Reference 20 represent average values for normal-weight, sand–lightweight, and all-lightweight concrete. However, computation of creep coefficients and shrinkage for the variables included in this study of reinforced thin-shell concretes, using only the correction factors shown above, indicate significant differences between predicted and measured values for the two lightweight concretes. Accordingly, the correction curves for unit weight shown in Figure 32 were developed from the test data to account for these differences. The computation procedures for the creep correction factors used to construct the curves in Figure 32 are shown in Tables 12 through 15. A summary of creep correction factors for the NCEL test conditions, based on Figures 27, 28, and 30, is shown in Table 12. Creep coefficients for 365 days (C_{365}) computed with Equation 3 and using the factors in Table 12 are shown in Table 13 for each of the test conditions at NCEL. Creep coefficients for 365 days computed by using NCEL test data are summarized in Table 14. Creep correction factors for unit weight are shown in the last line of Table 15 as the averages of the ratios of C_{365} (NCEL data) to C_{365} (Equation 3). These average ratios were used to construct the creep portion of Figure 32.

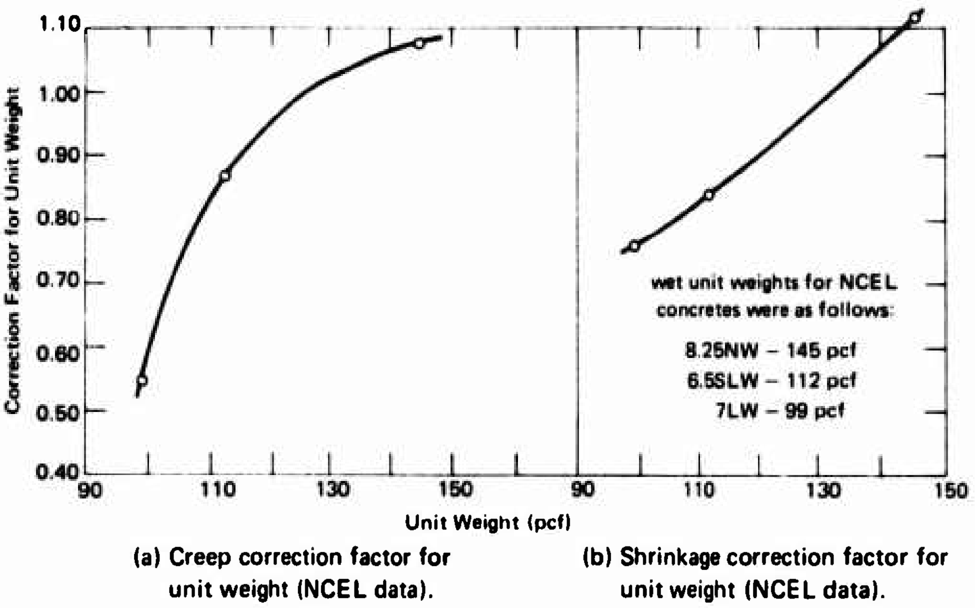


Figure 32. Creep and shrinkage correction factors for unit weight.

Table 12. Summary of Creep Correction Factors (Based on Figures 27, 28, and 30)

Parameter	Creep Correction Factor
Loading Age	
14 days	0.91
Storage environment	
25% RH	1.04
50% RH	0.94
70% RH	0.80
100% RH	0.60
Thickness, minimum	
1 inch	1.17
2 inches	1.14
4 inches	1.06

Table 13. Creep Coefficients for 365 Days (C_{365}) Computed by Equation 3 From Factors in Table 12

Age of Specimens (days)	Storage Environment (% RH)	Thickness of Specimens (in.)	Creep Coefficient, C_{365}
14	25	1	2.02[a]
		2	1.97
		4	1.82
	50	1	1.82
		2	1.78
		4	1.65
	70	1	1.55
		2	1.51
		4	1.40
	100	1	1.16
		2	1.13
		4	1.06

[a] $C_{365} = \frac{365^{0.10}}{10 + 365^{0.10}} (2.35 \times 0.91 \times 1.04 \times 1.17) = 2.02.$

Table 14. Creep Coefficients Based on NCEL Data

Age of Specimens (days)	Storage Environment (% RH)	Thickness of Specimens (in.)	Creep Coefficient,[a] C_{365}, for—		
			8.25NW Concrete	6.5SLW Concrete	7LW Concrete
14	25	1	1.92	1.18	1.05
		2	1.98	1.72	1.18
		4	1.88	1.50	0.68
	50	1	1.82	1.68	1.12
		2	1.78	1.58	1.05
		4	1.78	1.22	0.98
	70	1	1.75	1.25	0.82
		2	1.62	1.52	0.68
		4	1.52	1.20	none
	100	1	1.15	1.15	0.65
		2	1.48	1.02	0.62
		4	1.40	1.08	0.68

[a] Average of values for 0.25 and 0.50 stress–strength ratios from Tables 9, 10, and 11.

Table 15. Creep Correction Factors for Unit Weight

Age of Specimens (days)	Storage Environment (% RH)	Thickness of Specimens (in.)	Ratio of C_{365} From NCEL Data (Table 14) to C_{365} Computed by Equation 3 (Table 13) for—		
			8.25NW Concrete	6.5SLW Concrete	7LW Concrete
14	25	1	0.95[a]	0.58[b]	0.52
		2	1.00	0.87	0.60
		4	1.03	0.82	0.37
	50	1	1.00	0.94	0.62
		2	1.00	0.89	0.59
		4	1.08	0.74	0.62
	70	1	1.13	0.81	0.53
		2	1.07	1.00	0.45
		4	1.08	0.86	none
	100	1	1.00	1.00	0.56
		2	1.30	0.90	0.55
		4	1.32	1.02	0.64
Average correction factor			1.08	0.87	0.55

[a] 1.92 ÷ 2.02 = 0.95

[b] 1.18 ÷ 2.02 = 0.58

Correction factors for the shrinkage portion of Figure 32 (outlined in Tables 16 through 19) were determined in the same manner as the creep correction factors. The averages shown in the last line of Table 19 were used to construct the shrinkage portion of Figure 32.

All applicable correction factors must be used in any given situation to obtain the correct value of ultimate creep coefficient, C_u, or ultimate shrinkage, $(\epsilon_{sh})_u$, to use in Equations 3 or 4. Four illustrative examples of the use of the correction factors and Equations 3 and 4 are shown in Table 20. Examples 2, 3, and 4, for 8.25NW, 6.5SLW, and 7LW concrete, respectively, show excellent results for prediction of creep coefficients of all three concretes and for shrinkage of 8.25NW concrete, but only fair results for shrinkage of the lightweight concretes. It should be noted that the correction factors for unit weight (Tables 15 and 19) were average factors, and, therefore, some variations should be expected.

Table 16. Summary of Shrinkage Correction Factors
(Based on Figures 27, 29, and 31)

Parameter	Shrinkage Correction Factor
Loading Age	
14 days	0.95
Storage environment	
25% RH	1.19
50% RH	0.99
70% RH	0.78
Thickness, minimum	
1 inch	1.39
2 inches	1.25
4 inches	1.09

Table 17. Shrinkage Strain for 365 Days $(\epsilon_{sh})_{365}$ Computed
by Equation 4 From Factors in Table 16

Age of Specimens (days)	Storage Environment (% RH)	Thickness of Specimens (in.)	Shrinkage Strain, $(\epsilon_{sh})_{365}$ (μin./in.)
14	25	1	1,147[a]
		2	1,030
		4	900
	50	1	955
		2	860
		4	745
	70	1	750
		2	680
		4	590

[a] $(\epsilon_{sh})_{365} = \frac{365}{35 + 365}(800 \times 0.95 \times 1.19 \times 1.39) = 1{,}147\ \mu\text{in./in.}$

Table 18. Shrinkage Strain Based on NCEL Data

Age of Specimens (days)	Storage Environment (% RH)	Thickness of Specimens (in.)	Shrinkage Strain,[a] $(\epsilon_{sh})_{365}$ (in./in.)		
			8.25NW Concrete	6.5SLW Concrete	7LW Concrete
14	25	1	1,115	990	1,015
		2	975	895	965
		4	890	800	765
	50	1	1,035	700	670
		2	925	825	755
		4	810	725	505
	70	1	885	430	380
		2	785	695	520
		4	695	595	280

[a] From Table 8.

Table 19. Shrinkage Correction Factors for Unit Weight

Age of Specimens (days)	Storage Environment (% RH)	Thickness of Specimens (in.)	Ratio of $(\epsilon_{sh})_{365}$ From NCEL Data (Table 18) to $(\epsilon_{sh})_{365}$ Computed by Equation 4 (Table 17)		
			8.25NW Concrete	6.5SLW Concrete	7LW Concrete
14	25	1	0.97[a]	0.86	0.88
		2	0.95[b]	0.87	0.94
		4	0.99	0.89	0.85
	50	1	1.08	0.73	0.70
		2	1.08	0.96	0.88
		4	1.09	0.97	0.68
	70	1	1.18	0.57	0.51
		2	1.15	1.02	0.76
		4	1.18	1.01	0.47
Average correction factor			1.07	0.88	0.74

[a] 1,115 (Table 18) ÷ 1,147 (Table 17) = 0.97.

[b] 975 (Table 18) ÷ 1,030 (Table 17) = 0.95.

Table 20. Examples of Application of Correction Factors

Test Conditions		Creep Correction Factor	Shrinkage Correction Factor
Example 1: Hypothetical			
Loading age	28 days	0.84	0.91
Humidity	60% RH	0.87	0.80
Minimum thickness	8 in.	0.96	0.91
Unit weight	145 pcf	1.08	1.07
Total correction factor		0.76	0.71
Correction for C_u: 2.35 x 0.76 = 1.79 (to be used in Equation 3)			
Correction for $(\epsilon_{sh})_u$: 800 x 0.71 = 568 (to be used in Equation 4)			
Example 2: 8.25NW Concrete			
Loading age	14 days	0.91	0.95
Humidity	50% RH	0.94	0.99
Minimum thickness	2 in.	1.14	1.25
Unit weight	145 pcf	1.08	1.07
Total correction factor		1.05	1.26
Equation 3: $C_{365} = [365^{0.60}/(10 + 365^{0.60})]\ (2.35)\ (1.05) = 1.96$; from Table 9, $C_{365} = 1.75$ to 1.80			
Equation 4: $(\epsilon_{sh})_{365} = [365/(35 + 365)]\ (800)\ (1.26) = 920\ \mu$in./in.; from Table 8, $(\epsilon_{sh})_{365} = 925\ \mu$in./in.			
Example 3: 6.5SLW Concrete			
Loading age	14 days	0.91	0.95
Humidity	50% RH	0.94	0.99
Minimum thickness	2 in.	1.14	1.25
Unit weight	112 pcf	0.87	0.88
Total correction factor		0.85	0.98
Equation 3: $C_{365} = [365^{0.60}/(10 + 365^{0.60})]\ (2.35)\ (0.85) = 1.55$; from Table 10, $C_{365} = 1.50$ to 1.65			
Equation 4: $(\epsilon_{sh})_{365} = [365/(35 + 365)]\ (800)\ (1.03) = 751\ \mu$in./in.; from Table 8, $(\epsilon_{sh})_{365} = 825\ \mu$in./in.			

continued

Table 20. Continued

Test Conditions		Creep Correction Factor	Shrinkage Correction Factor
Example 4: 7LW Concrete			
Loading age	14 days	0.91	0.95
Humidity	50% RH	0.94	0.99
Minimum thickness	2 in.	1.14	1.25
Unit weight	99 pcf	0.55	0.74
Total correction factor		0.54	0.87

Equation 3: $C_{365} = [365^{0.60}/(10 + 365^{0.60})]\ (2.35)\ (0.54) = 0.98$;
from Table 11, $C_{365} = 1.05$

Equation 4: $(\epsilon_{sh})_{365} = [365/(35 + 365)]\ (800)\ (0.87) = 635\ \mu$in./in.;
from Table 18, $(\epsilon_{sh})_{365} = 755\ \mu$in./in.

An example is given below of the application of the above equations and procedures in determination of the deflection of reinforced concrete one-way slabs:[22]

For deflection due to creep only $\Delta_t = k_r C_t \Delta_i$ **(5)**

For deflection due to creep and shrinkage $\Delta_t = d_r T \Delta_i$ **(6)**

where C_t = creep coefficient determined from Equation 3 (with corrections for C_u)

Δ_i = initial deflection

Δ_t = deflection at any time, t

k_r = reduction factor to account for compression reinforcing steel, movement of neutral axis, and progressive cracking. For creep only, $k_r = 0.85 - 0.45\ (A_s'/A_s)$ but not less than 0.40. For creep and shrinkage, $k_r = 1 - 0.60\ (A_s'/A_s)$ but not less than 0.40.

T = multiplier for additional long-time deflection due to creep and shrinkage: $k_r T = 2.0$ when $A_s' = 0$, using Equation 8[24]
$k_r T = 1.4$ when $A_s'/A_s = 0.5$, using Equation 8[24]
$k_r T = 0.8$ when $A_s'/A_s = 1$, using Equation 8[24]

A_s = area of tension reinforcing steel

A_s' = area of compression reinforcing steel

FINDINGS AND CONCLUSIONS

1. Generally speaking, creep-plus-shrinkage and shrinkage were highest in normal-weight concrete, slightly less in sand–lightweight concrete, and least in all-lightweight concrete. Creep, on the other hand, was highest in sand–lightweight concrete and lowest in all-lightweight concrete.

2. Creep coefficients for the normal-weight concrete were somewhat higher than those for the lightweight concretes, probably reflecting the differences in moduli of elasticity and the effects of water absorbed by the lightweight aggregate.

3. Time-dependent strains of reinforced thin-shell concrete made with mixes similar to those reported herein can be predicted for any combination of variables on the basis of the ratio of exposed surface area to volume as described herein.

4. The zinc coating on galvanized reinforcing is oxidized in a concrete environment. The highest percentages of oxidation were found in 7LW all-lightweight concrete.

5. Predicted values for creep coefficients and shrinkage based on equations and correction factors recommended by ACI Committee 209 together with correction factors for unit weight developed in this study were in good to excellent agreement with observed data.

RECOMMENDATION

The equations and procedures for computing creep and shrinkage allowances reported herein should be used by designers for thin-shell sections as well as for prestressed and other reinforced concrete structures.

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Appendix

DETAILS OF CONCRETE MIXES

Pertinent data on the concrete mixes are shown in Table 21. The batches were made in a pan-type laboratory mixer in quantities of 1.4 to 1.5 ft^3. Mixing procedures are given below.

8.25NW Concrete

1. Mix aggregate and cement dry for 30 seconds.
2. Add water and mix for 2-1/2 minutes.
3. Measure slump and add water if necessary.

6.5SLW Concrete

1. Soak coarse aggregate (expanded shale) for 10 minutes in about 2/3 of the mixing water.
2. Add fine aggregate and air-entraining agent.
3. Mix for 30 seconds.
4. Add cement and remainder of mixing water.
5. Mix for 3 minutes.
6. Let concrete stand for 5 minutes.
7. Remix for 10 seconds.
8. Measure air content and slump and add water if needed.

7LW All-Lightweight Concrete

1. Soak coarse aggregate (expanded shale) for 3 minutes in about 2/3 of mixing water.
2. Add expanded shale sand and soak for 10 minutes.
3. Add air-entraining agent and mix for 30 seconds.
4. Add cement and remainder of mixing water and mix for 3 minutes.
5. Let concrete stand for 5 minutes.
6. Remix for 10 seconds.
7. Measure air content and slump and add water if needed.

Table 21. Pertinent Concrete Mix Data (Based on 1 yd^3)

Item	Concrete Mix		
	8.25NW	6.5SLW	7LW
Coarse aggregate	1,270 lb 3/8-inch minus Santa Clara River gravel	738 lb 3/8-inch minus expanded shale	720 lb 3/8-inch minus expanded shale
Fine aggregate	1,620 lb Santa Clara River concrete sand	1,278 lb Santa Clara River concrete sand	845 lb expanded shale sand
Cement (type III, portland)	775 lb = 8.25 sacks	611 lb = 6.5 sacks	658 lb = 7 sacks
Water	343 lb ≈ 41 gal	330 lb = 40 ± 1/2 gal	338 lb = 40 ± 1/2 gal
Air-entraining agent	none	162 ml neutralized vinsol resin in liquid as supplied by manufacturer	207 ml neutralized vinsol resin in liquid as supplied by manufacturer
Average air content	not measured	5.3%	5.4%
Water—Cement Ratio	0.44 ≈ 5 gal/sack	0.53 ≈ 6 gal/sack	0.51 ≈ 5.7 gal/sack
Slump	3 inches	3 inches	3 inches
Unit weight (wet)	148 pcf	112 pcf	99 pcf
Compressive strength[a] (3 x 6-inch cylinder)	6,220 psi	5,490 psi	5,580 psi
Modulus of elasticity[a]	3.33 psi x 10^6	2.46 psi x 10^6	2.03 psi x 10^6

[a] At 14 days of age after 14 days of curing in 100% RH.

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13. ABSTRACT

Creep coefficients and shrinkage factors were determined for specimens of three thin-shell reinforced concretes consisting of one normal-weight concrete, one sand–lightweight concrete, and one all-lightweight concrete. Prismatic specimens were tested in thicknesses of 1 inch, 2 inches, and 4 inches at stress–strength ratios of 0.25 and 0.50. Specimens were tested in controlled relative humidities of 25%, 50%, 70%, and 100%, with temperature at 73°F in all locations. Curves involving surface-area-to-volume ratios were used to determine time-dependent strains for different humidities, sizes, and stresses. Equations are presented for creep coefficients and for shrinkage; curves are presented for obtaining correction factors to be used in design equations. Correction curves for unit weight were developed with test data from this study. Predicted values for creep coefficients and shrinkage agreed with observed data when computed with equation and correction factors presented herein.

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